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DOCUMENT NO D6-58362TN

TITLE: Bulk Modulus Investigation - Hydraulic Fluid Stiffness

MODEL General

ISSUE NO. 7 TO: DDC #1 (DATE)

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		(DATE)

SUBJECT INDEX (A) HYDRAULIC FLUID STIFFNESS

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I. ABSTRACT

Isothermal secant bulk modulus data was obtained from simulated hydraulic systems and compared with referenced data. Reference sources have been the only available data from which to select bulk modulus values for system and component design. Therefore a definite need existed for additional information as design values are presently selected arbitrarily or from experience. Often these values are arbitrarily modified for certain system design and vary greatly with the experience of the designer. This study was made to compare the amount of fluid compressibility existing within a typical airplane hydraulic system and within a standard bench test system. Additional comparisons were made with published reference sources.

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II. SUMMARY

This study was made to compare the amount of fluid compressibility existing within a typical airplane hydraulic system and within a standard bench test system. Additional comparison was made with published reference sources. As these reference sources have been the only available data from which to select bulk modulus (compressibility factor) values for system and component design, a definite need for additional information exists because presently these values are often arbitrarily modified for system design and vary with the experience of the designer.

Bulk modulus, a measure of fluid compressibility, is an important fluid property in the design of systems employing fluid for force transmission and motion control. The fluid, acting as a spring in a spring-mass system affects such system factors as response time, force available from limited stroke actuators, and stability of servocontrolled hydraulic systems.

The form of bulk modulus most commonly found in reference sources is the isothermal secant bulk modulus. It is defined as the total change in fluid pressure divided by the total change in fluid volume per unit volume under pressure at a constant temperature. It is expressed by the following relation:

$$B_t = -\frac{\Delta P}{\frac{\Delta V}{V}} \quad psi$$

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It is defined graphically as the slope of the line connecting two pressures of a pressure versus $\Delta V/V$ curve (Figure 1). For our

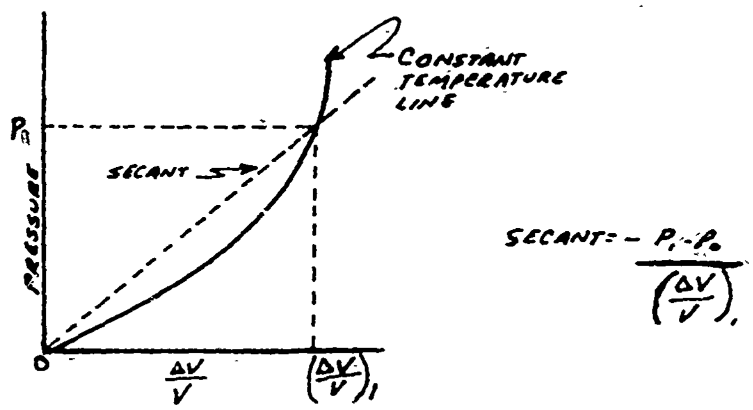


Figure 1 Definition of Secant Bulk Modulus

computations, one pressure was equal to zero.

In this investigation two laboratory systems were employed to develop fluid compressibility, a simulated flight control (hydraulic) system and a conventional static bench system. The Pressure-Volume-Temperature method was used in both systems to obtain the bulk modulus data. With this method a change in oil volume is measured for a given pressure change, yielding a static bulk modulus value.

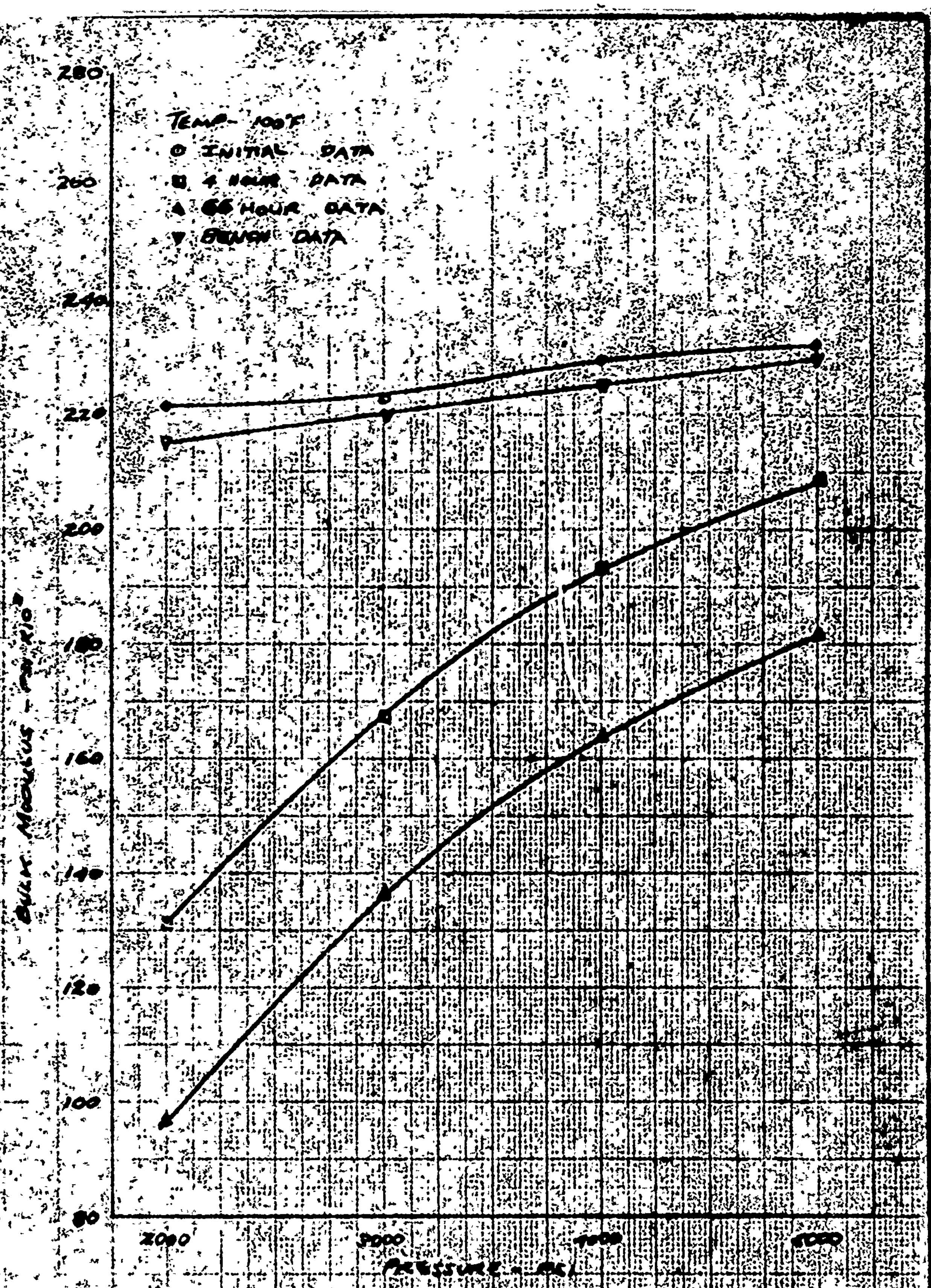
The fluids used in this study were MIL-H-5606B, WSX-6885, and Skydrol 500A. The WSX-6885 fluid is under consideration for use in the Supersonic Transport. The MIL-H-5606B and Skydrol 500A are production fluids in general use in military and commercial aircraft.

For the three fluids tested, the bench values compared with the published data within acceptable margins. Comparisons of the hydraulic system data resulted in different trends for the three fluids. With the MIL-H-5606B fluid, the initial values were the highest, the four hour values, the lowest (Figure 2). For both the WSX-6885 and Skydrol 500A fluids, the initial values were the highest, followed by the 4 hour and 18 hour values in decreasing order (Figure 3). With a 100 psi dormant period test section pressure, the bulk modulus values were repeatable within the range of test tolerances for both WSX-6885 and Skydrol 500A fluids.

In order to determine if system cycling will restore the value of bulk modulus to its initial value following dormant unpressurized periods, two full stroke cycles were conducted after data was taken at four hours. Following bulk modulus measurements, two more cycles and measurements were made. In three of the four tests conducted with WSX-6885 and Skydrol 500A fluids, complete recovery from the lower four hour values to the initial values was made following the four cycles.

The air content of the fluid and its variation with cycling was investigated by the use of a Seaten Wilson "Aircmeter." A negligible difference existed between cycled and uncycled fluid.

The bulk modulus of a flowing fluid was also obtained. In determining this bulk modulus, the wave speed of a disturbance induced in the fluid



			REVISED	DATE	
CALC					TYPICAL SYSTEM BULK MODULUS DATA - MIL-H-5606B
CHECK					FIG 2
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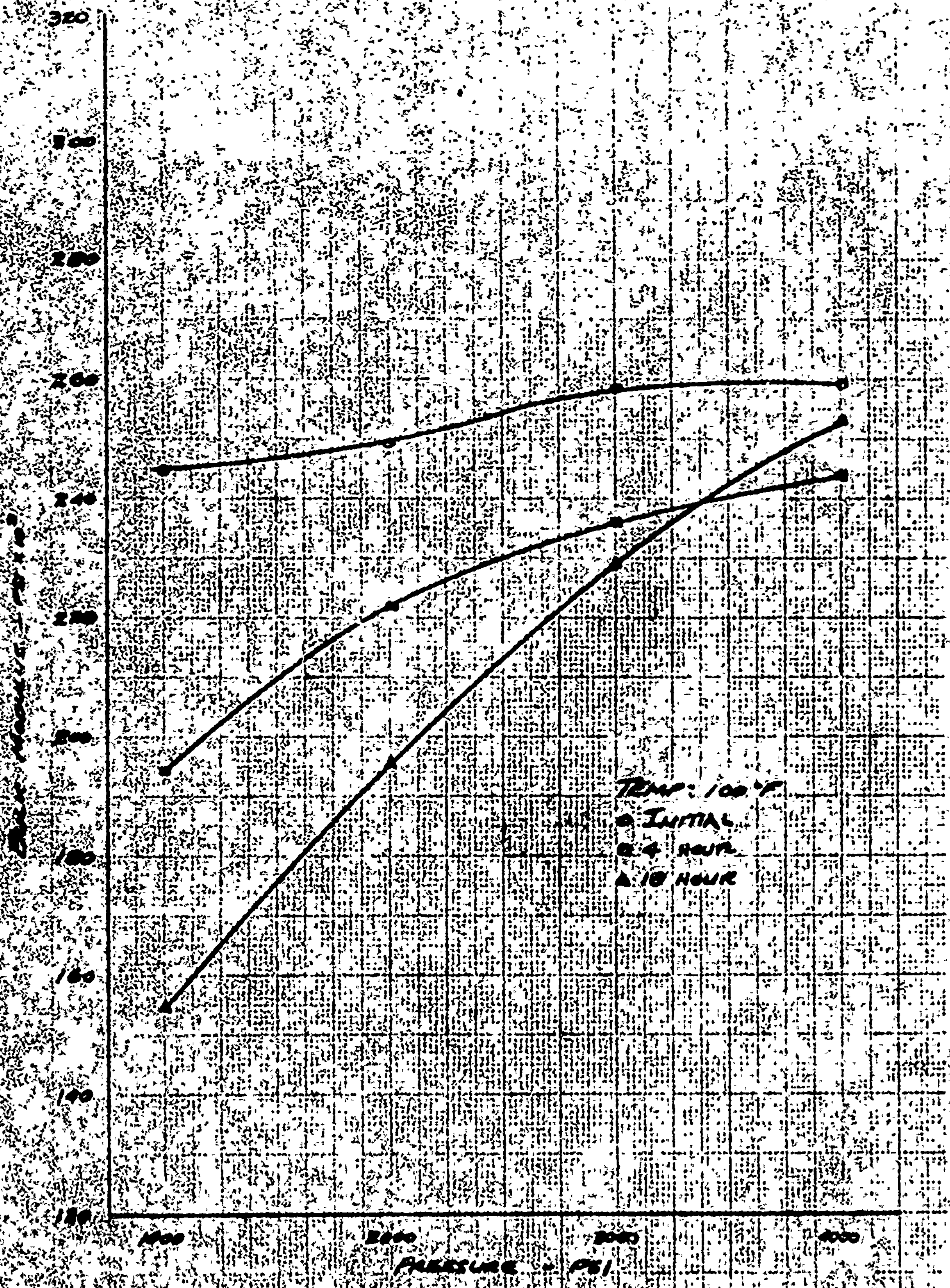

CALC			REVISED	DATE	TYPICAL SYSTEM BULK MODULUS DATA V/SX-6885	FIG 3
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is measured and combined with the fluid density and tubing correction factors to obtain an adiabatic bulk modulus as expressed by the relation:

$$\bar{B}_s = \frac{\rho a^2 E t'}{E t' - D \rho a^2 C_1} \qquad \text{(See Appendix A)}$$

where "a" is the wave speed.

Based on the data obtained, the following conclusions are realized.

1. For system conditions involving dormant unpressurized periods, as in utility systems, the fluid bulk modulus is initially low but approaches the published value within the first moments of system actuation.

2. Dissolved and entrained air or gas remaining within a hydraulic system which is continuously pressurized has no appreciable effect on the fluid bulk modulus and consequently the system stiffness. This effect applies to primary flight control systems and to systems in which the actuator remains pressurized but inactive over extended time periods.

3. Acceptable correlation was obtained between our bench measurements and published data for MIL-H-5606B and WSX-6885 fluids. With Skydrol 500A an accurate assessment was difficult to realize due to the inconsistency of the published data available.

4. The system measurements produced initial values which compared very favorably with the bench results for the three fluids tested.

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5. The system measurements following pressurized dormant periods yielded the most accurate correlation with the initial system values and subsequently the bench and published values.

6. The method employed to measure the bulk modulus of a flowing fluid also produced acceptable results for both WSX-6885 and Skydrol 500A fluids.

III. INTRODUCTION

This investigation arose from the need to obtain additional information on bulk modulus of a fluid in a hydraulic system, as the value of bulk modulus used in calculations is often arbitrary or selected on the basis of experience. Bulk modulus is a measure of the compressibility of a fluid, and is an important fluid property in system design as it affects such system factors as response time, force available from limited stroke actuators and stability of hydraulic servos and servo-controlled hydraulic systems.[1] The data compiled in this document should provide an insight into the behavior of bulk modulus under actual operating conditions.

II. DISCUSSION

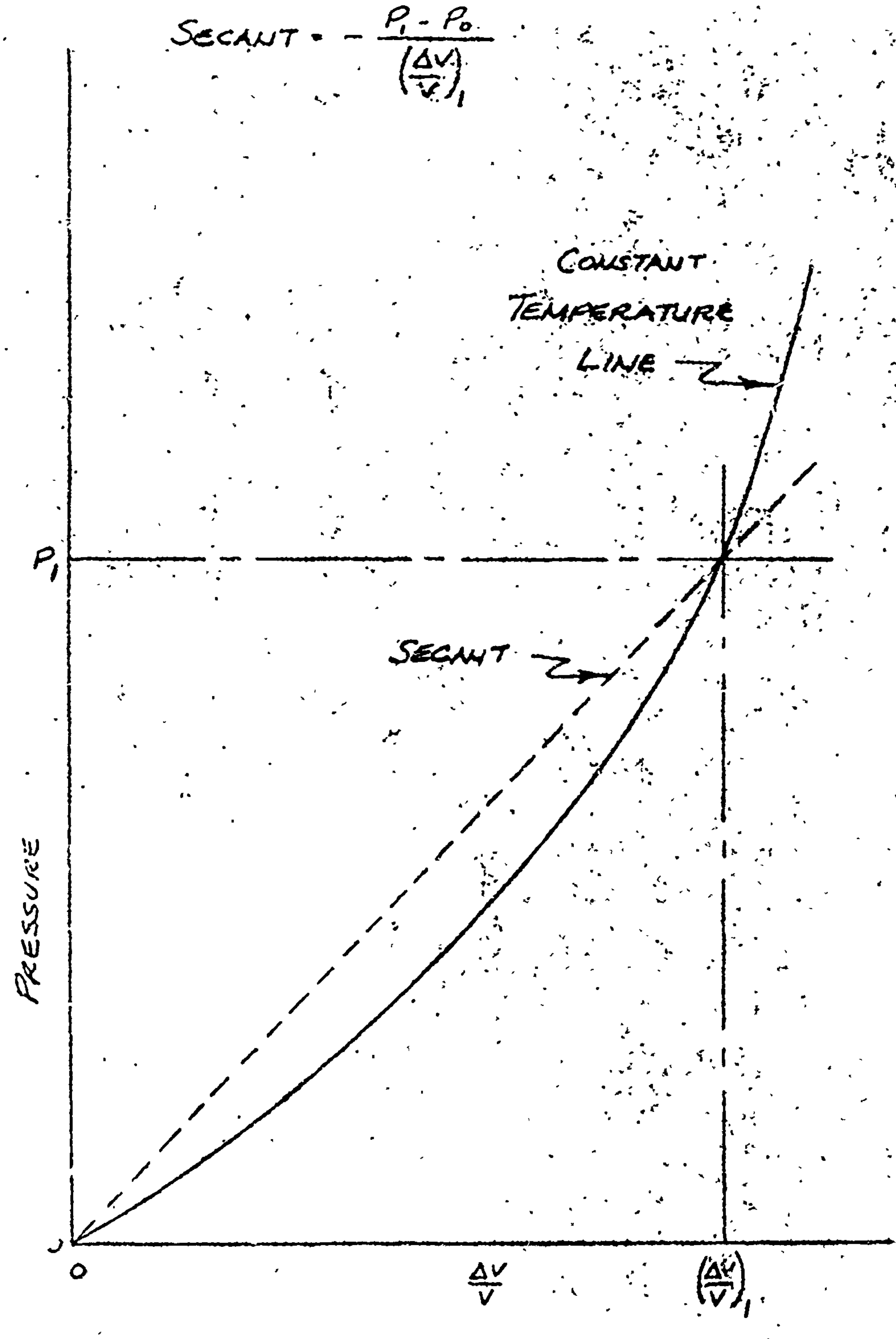
Isothermal secant bulk modulus, one of several forms of bulk modulus and a measure of fluid stiffness, is the most commonly found form in reference sources. It is defined as the total change in fluid pressure divided by the total change in fluid volume per unit volume under pressure at constant temperature. The equation for this form of bulk modulus is

$$B_t = \frac{\Delta P}{\frac{\Delta V}{V}_t} \quad PSI$$

Graphically, it is defined as the slope of the line connecting two pressures of a pressure versus $\Delta V/V$ curve (Figure 4).

In this investigation, fluid isothermal secant bulk modulus values were obtained for three fluids at various temperatures and pressures. Measurements were made both in a standard bench fixture and in a hydraulic servo-actuator system. The purpose of using two systems was to investigate any variations in bulk modulus obtained with fluid contained within a simulated flight control system and values obtained in conventional static tests. The fluids used were MIL-H-5606B, WSX-6885, and Skydrol 500A. The WSX-6885 fluid is under consideration for use in the Supersonic Transport while the other two are production fluids in general use in military and commercial aircraft.

The Pressure-Volume-Temperature method was used to obtain the data. This method yields the volume change for a pressure change exerted on a given initial fluid volume. The values obtained can be substituted in the relation above to obtain the bulk modulus value.



ENGR.			REVISED	DATE	DEFINITION OF SECANT BULK MODULUS	FIG 4
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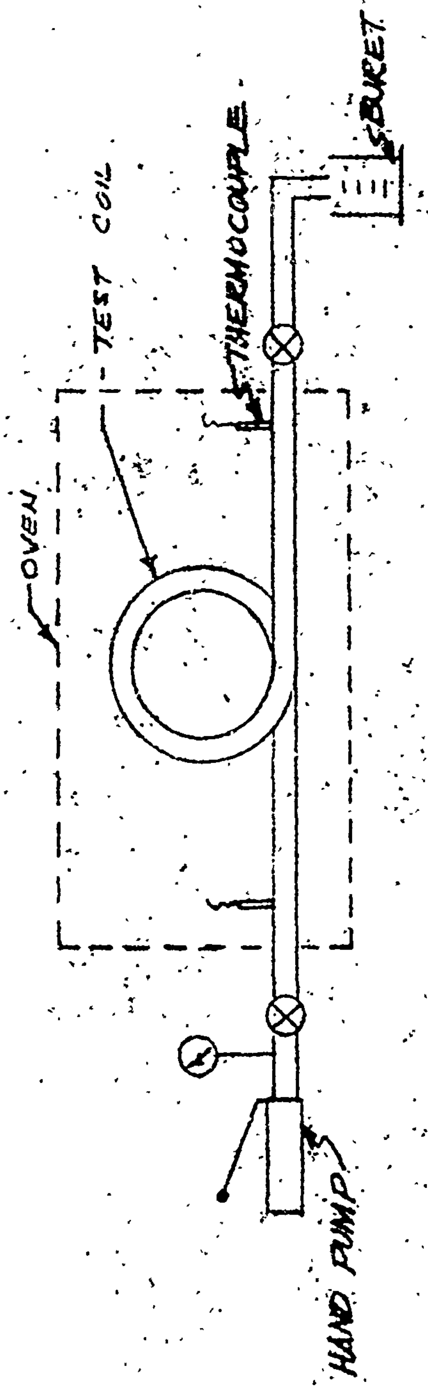
A. Description of Test

The bench fixture consisted of a coil of tubing as the test section and a hand pump and associated equipment (Figures 5 through 7). This system has been used in previous tests at Boeing for the measurement of fluid bulk modulus values. The hydraulic system employed a servo-controlled single-ended actuator loaded by a torsion bar. The test section comprised the actuator to servo-valve tubing and is pressurized by a hand pump connected to the head end of the actuator (Figures 8 through 10). Measurement procedures are identical for both systems.

In selecting the tubing as the test section instead of the actuator, the following criteria were used. In using the actuator with the head end comprising the test cavity, the piston seal leakage and structural compliance of the actuator could not be accurately determined for all conditions investigated. The leakage is directly related to the bore-to-seal clearance. This clearance is affected by pressure, structural compliance of the barrel, longitudinal position of the seal in the barrel, and the seal wear. In addition, a suitable means of locking the piston-rod was necessary. The use of tubing alleviates these problems as a leak-tight chamber could be attained between two valves and the compliance of the tubing could be determined mathematically. Because the test section comprised the rod end to servo-valve tubing, it was assumed that the fluid in this section and in the actuator is subjected to nearly identical conditions. Therefore, the bulk modulus values obtained are representative of the fluid bulk modulus in the actuator.



ENGR.			REVISED	DATE	BENCH SYSTEM	FIG 5
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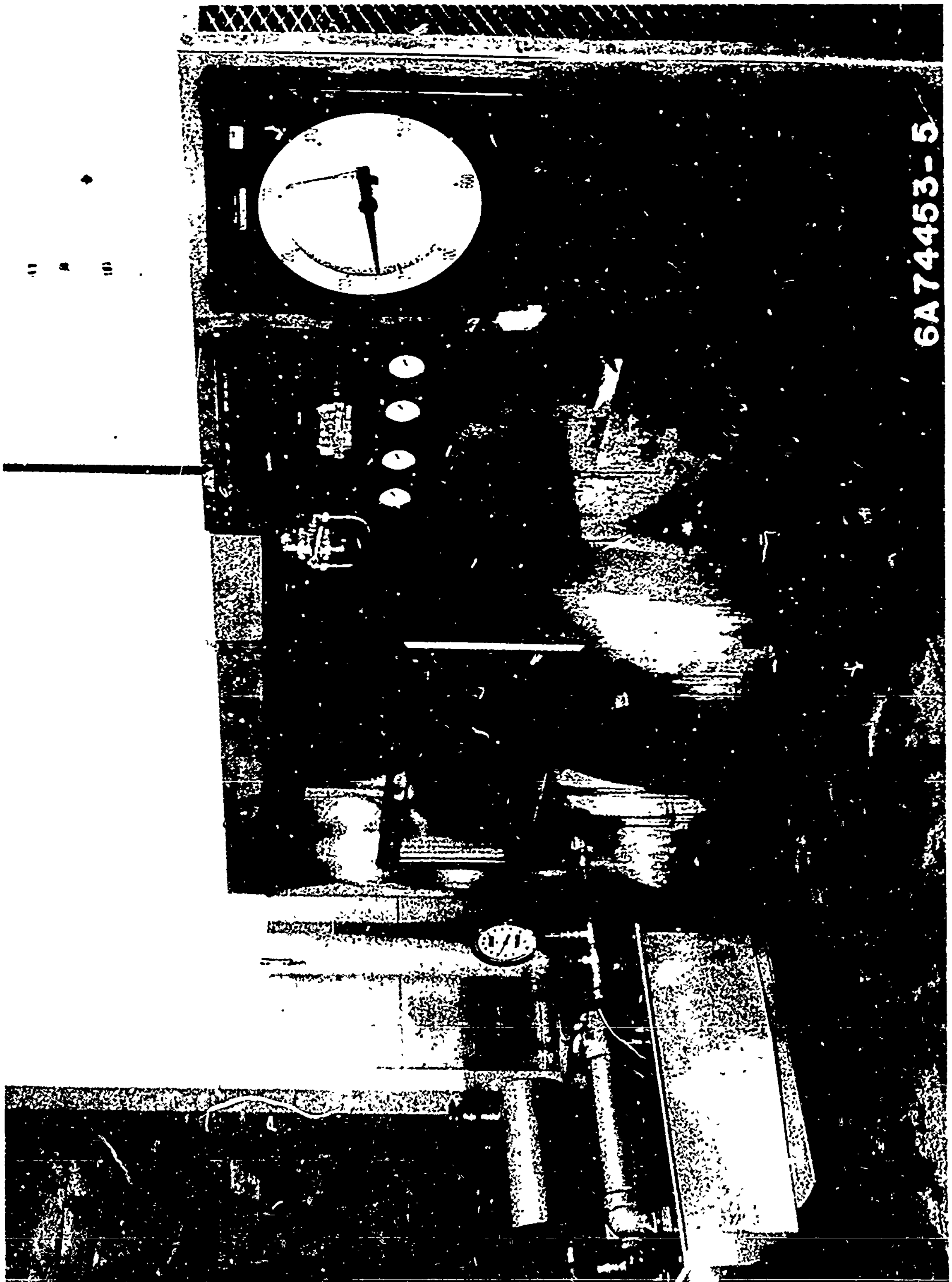
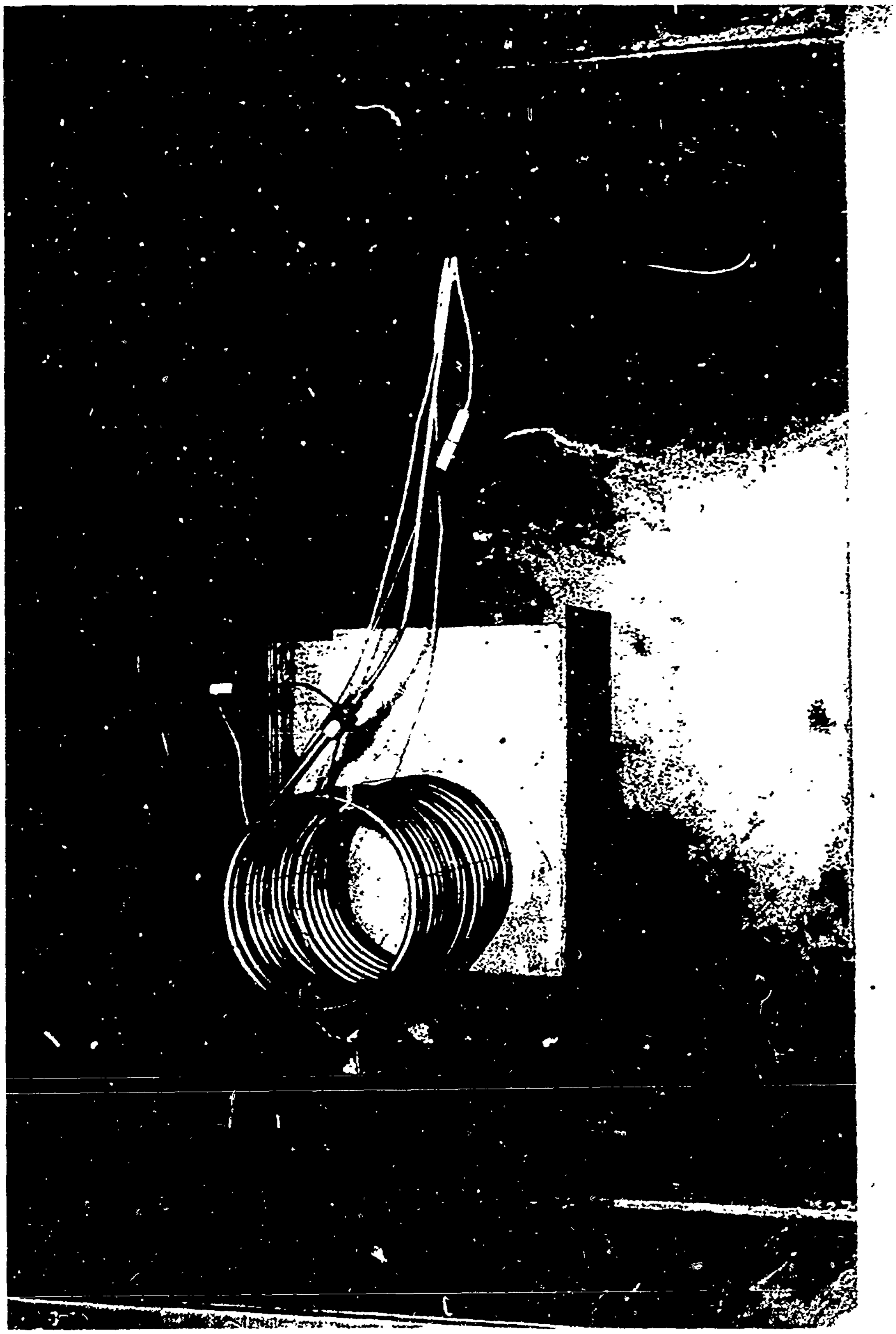
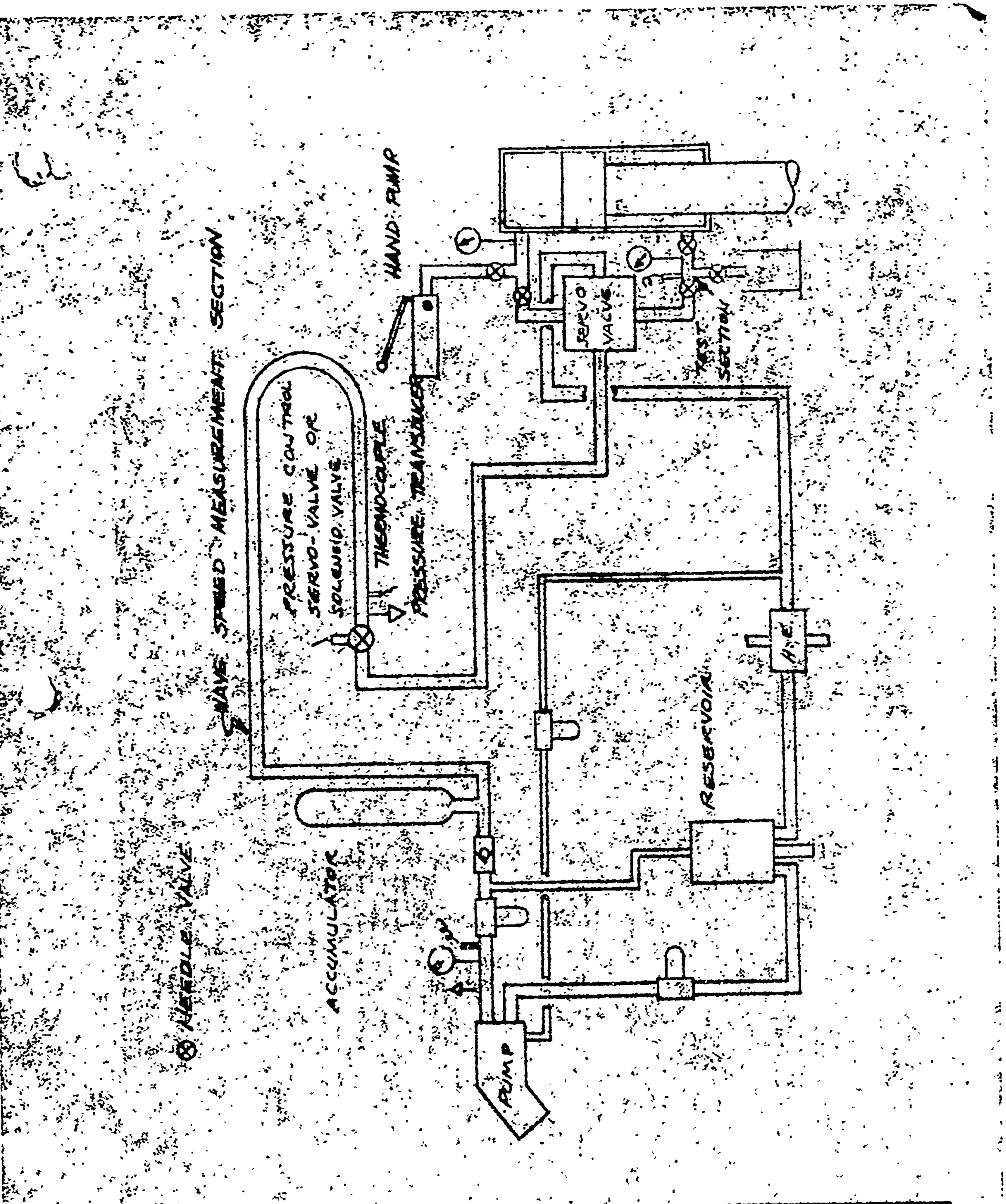


BENCH SYSTEM - BULK MODULUS INVESTIGATION FIG 6



BENCH SYSTEM - BULK MODULUS INVESTIGATION FIG. 7



ENGR.	Lius	3/27/67	REVISED	DATE	TEST SYSTEM BULK MODULUS INVESTIGATION	FIG 8 D6-58362TN
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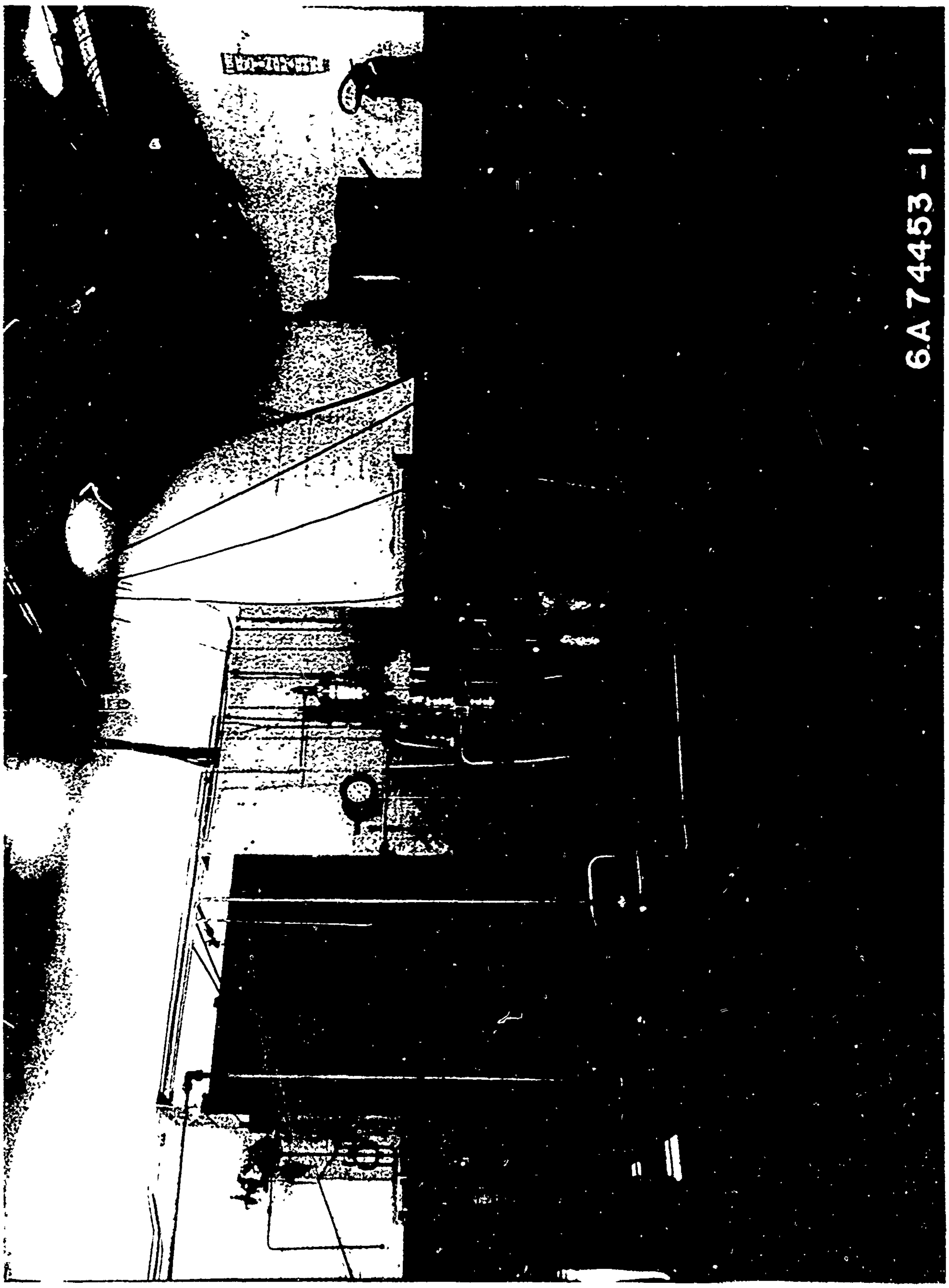
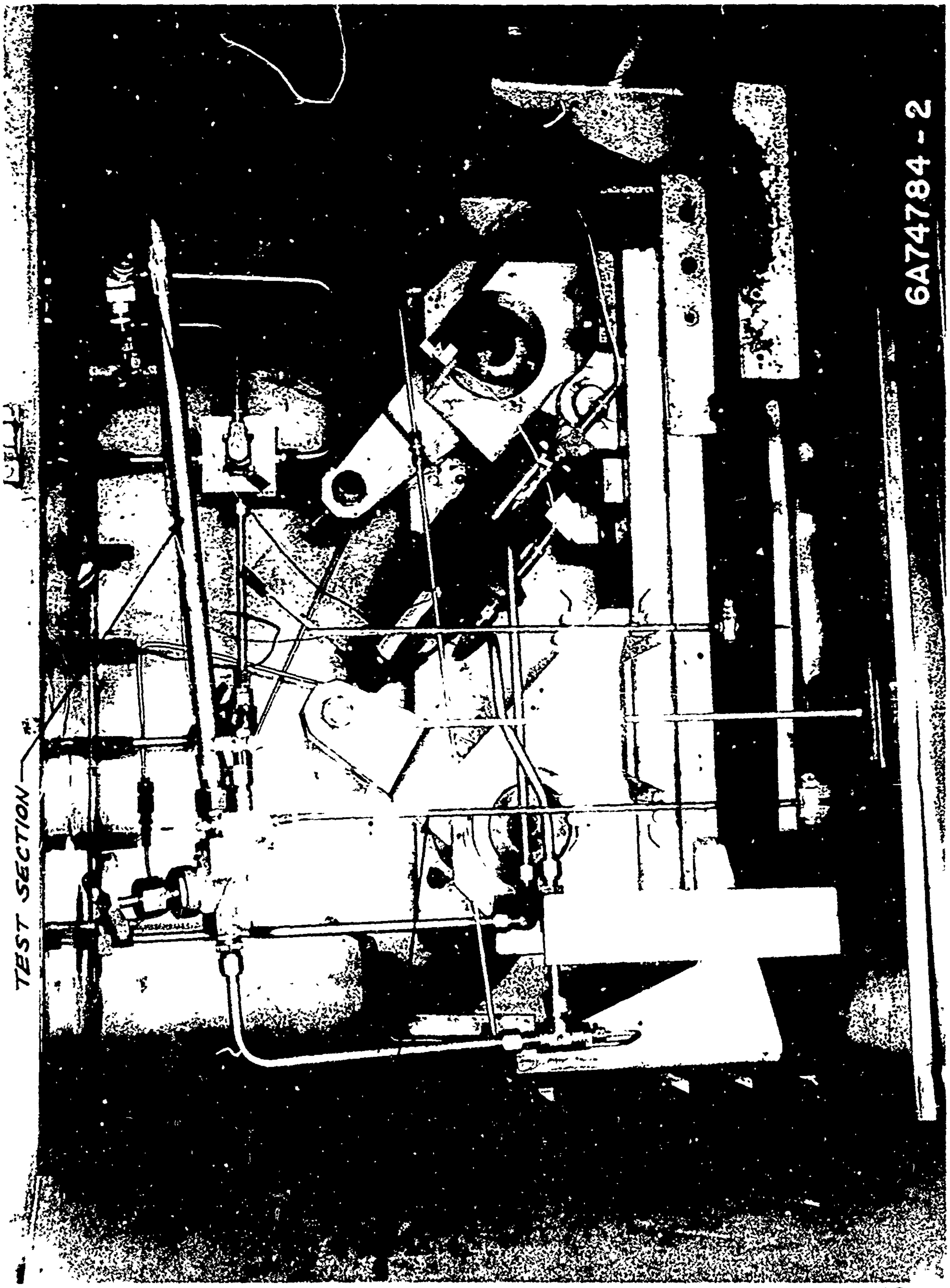


TEST SYSTEM - BULK MODULUS INVESTIGATION FIG 9



TEST SYSTEM - BULK MODULUS INVESTIGATION FIG 10

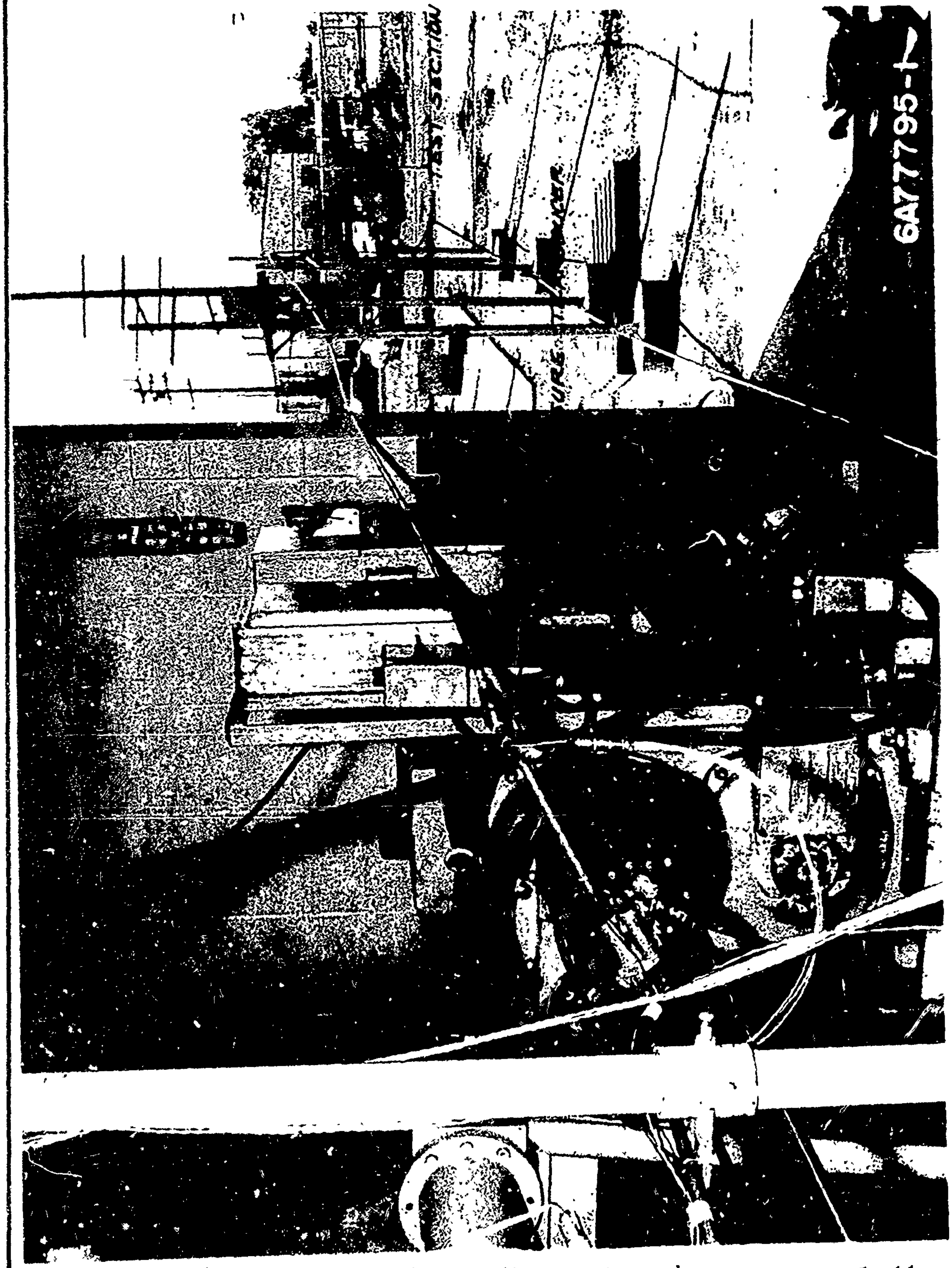
In addition to the above static values, the bulk modulus was also obtained for a flowing fluid by means of wave speed measurements. For measurement of the bulk modulus, a section of tubing approximately 100 feet in length was incorporated in the servo-actuator system adjacent to the pump. This section was equipped with a solenoid valve for testing of WSX-6385 and a pressure control servo-valve for Skydrol 500A fluids. Pressure transducers were incorporated in each end of the test section to determine the elapsed wave travel time of the disturbance created by closure of the valves. (Figure 11 and 12). The wave travel time was utilized to determine the wave speed of the disturbance. The heating and cooling effect generated by compression and expansion waves occurs very rapidly and may be considered an adiabatic process.[2,3] Therefore, the wave speed in conjunction with the fluid density and tubing correction factors yields an adiabatic bulk modulus when substituted into the relation

$$\bar{B}_s = \frac{\rho a^2 E t'}{E t' - D \rho a^2 C_1} \qquad \text{(See Appendix A)}$$

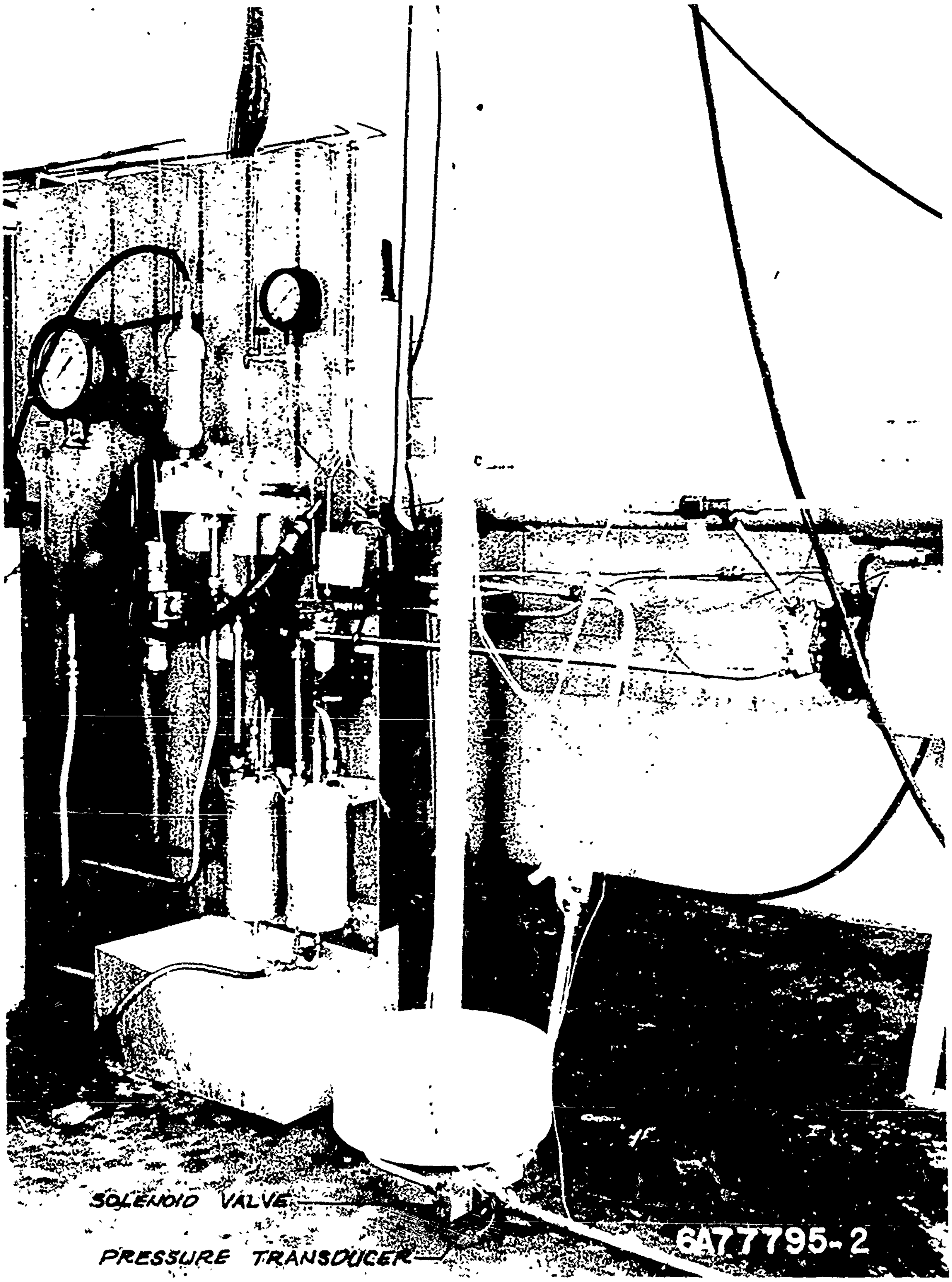
in which "a" is the wave speed of the disturbance.[4]

B. <u>Test Procedure</u>

The data was taken under the following conditions for the three fluids under consideration.



SYSTEM - WAVE SPEED MEASUREMENT SECTION FIG 11



TEST SYSTEM - WAVE SPEED MEASUREMENT SECTION FIG 12

Fluid	Pressure psi X 1,000					Temperature	Test Fixture
	1	2	3	4	5		
MIL-H-5606B		X	X	X	X	70 F, 200 F	Bench
		X	X	X	X	100 F, 200 F	System
WSX-6885	X	X	X	X		100 F, 350 F	Bench
	X	X	X	X		100 F, 350 F	System
			X			100 F, 200 F	1
Skydrol 500A	X	X	X	X		100 F, 200 F	Bench
	X	X	X	X		100 F, 200 F	System
			X			100 F, 200 F	1

1 Wave speed measurements with a flowing fluid.

In order to determine if system cycling will restore the value of bulk modulus to its initial value following dormant unpressurized periods, two full stroke cycles were conducted after data was taken at four hours. Following bulk modulus measurements, two more cycles and measurements were made. This sequence was performed at 100 F and 350 F and at 100 F and 200 F for WSX-6885 and Skydrol 500A fluids respectively with measurements being made at 1000 and 3000 psi.

Bulk modulus measurements were made three times at each temperature and series of pressures for each specific fluid. System cycling was conducted for fifteen minutes prior to the initial measurements. Following a four hour dormant period at zero pressure, the bulk modulus measurements were repeated. A final measurement was made after a second dormant period of 18 to 114 hours. This procedure was followed for all three fluids and, in addition, was repeated for WSX-6885 and Skydrol 500A with a pressure of 100 psi on the test section during the dormant periods.

Extended cycling with MIL-H-5606B was also conducted for periods of 7 and 14 hours. Bulk modulus measurements were made at a temperature of 200 F and pressures of 2000, 3000, 4000, and 5000 psi. The dormant periods were conducted at zero pressure. Following the extended cycling the system was drained and refilled with new MIL-H-5606B fluid and the bulk modulus measurements repeated under the previously mentioned procedure.

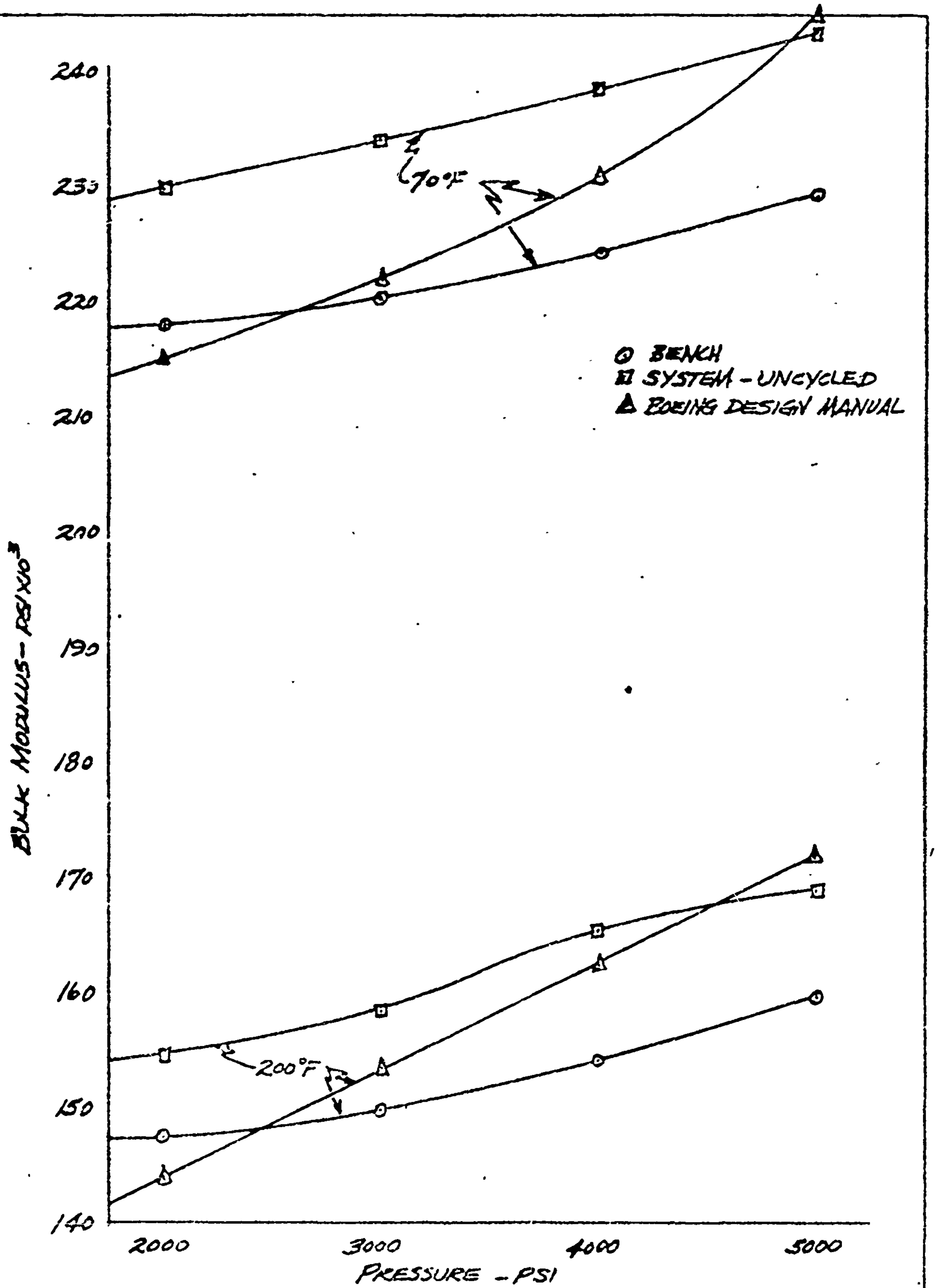
C. Test Results

1. Bench and System Tests

In comparing the bulk modulus values obtained with MIL-H-5606B, the bench data and system data for uncycled fluid yielded curves of the same general slope. The system values exceeded the bench values (Figure 13). Although the numerical values are noticeably different, the deviation did not exceed 7.5 percent (Figure 14). In comparing this data with published data from The Boeing Design Manual, the difference in curve slope is considerable (Figure 15). However, the maximum deviation between the bench and published data was less than 8 percent (Figure 15).

In comparison of the hydraulic system data, the initial values were the highest; the four hour values, the lowest (Figures 16 through 22). The 18 to 114 hour values were between the initial and four hour data with the exception of two cases in which these values were less than the four hour values (Figures 18 and 19).

Although the fluid volumes in the bench and system test differed by a factor of approximately three, the ΔV's recorded differed



CALC			REVISED	DATE	COMPARISON OF BENCH, SYSTEM, & PUBLISHED DATA - MIL-H-5606B	FIG. 13
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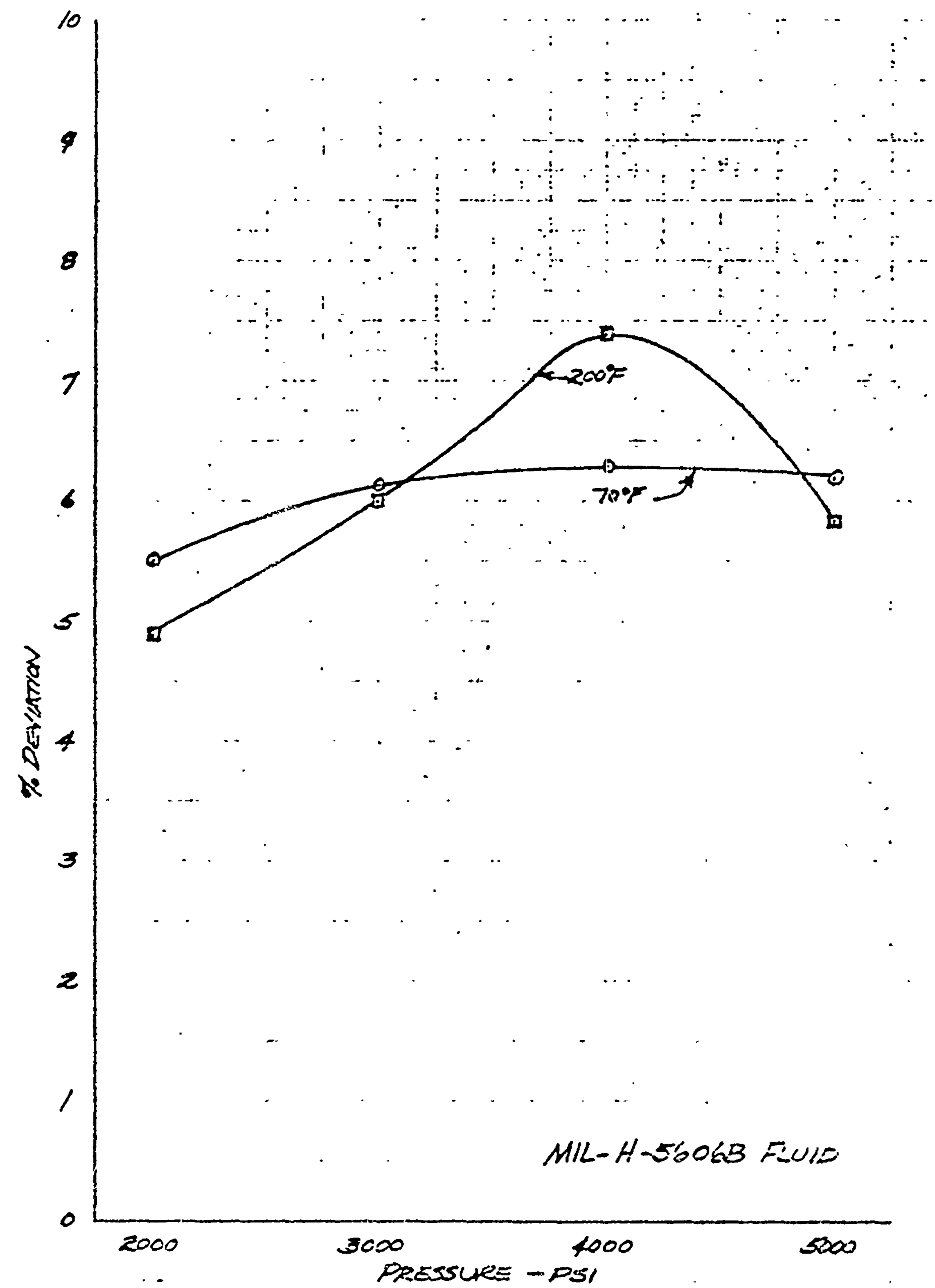

DEVIATION BETWEEN BENCH AND SYSTEM BULK MODULUS

FIG 14

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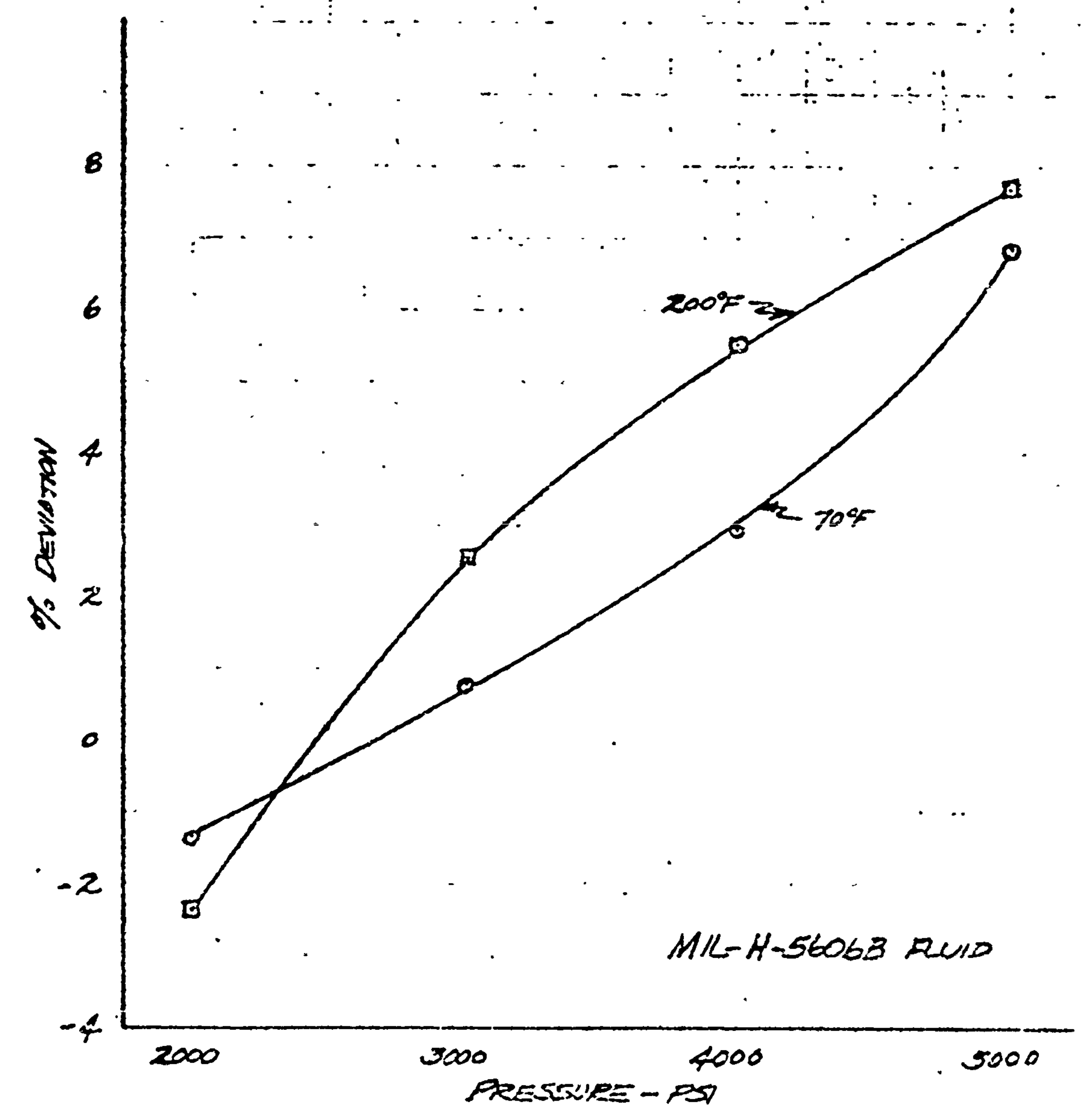

CALC			REVISED	DATE	DEVIATION BETWEEN BENCH AND PUBLISHED BULK MODULUS	FIG 15
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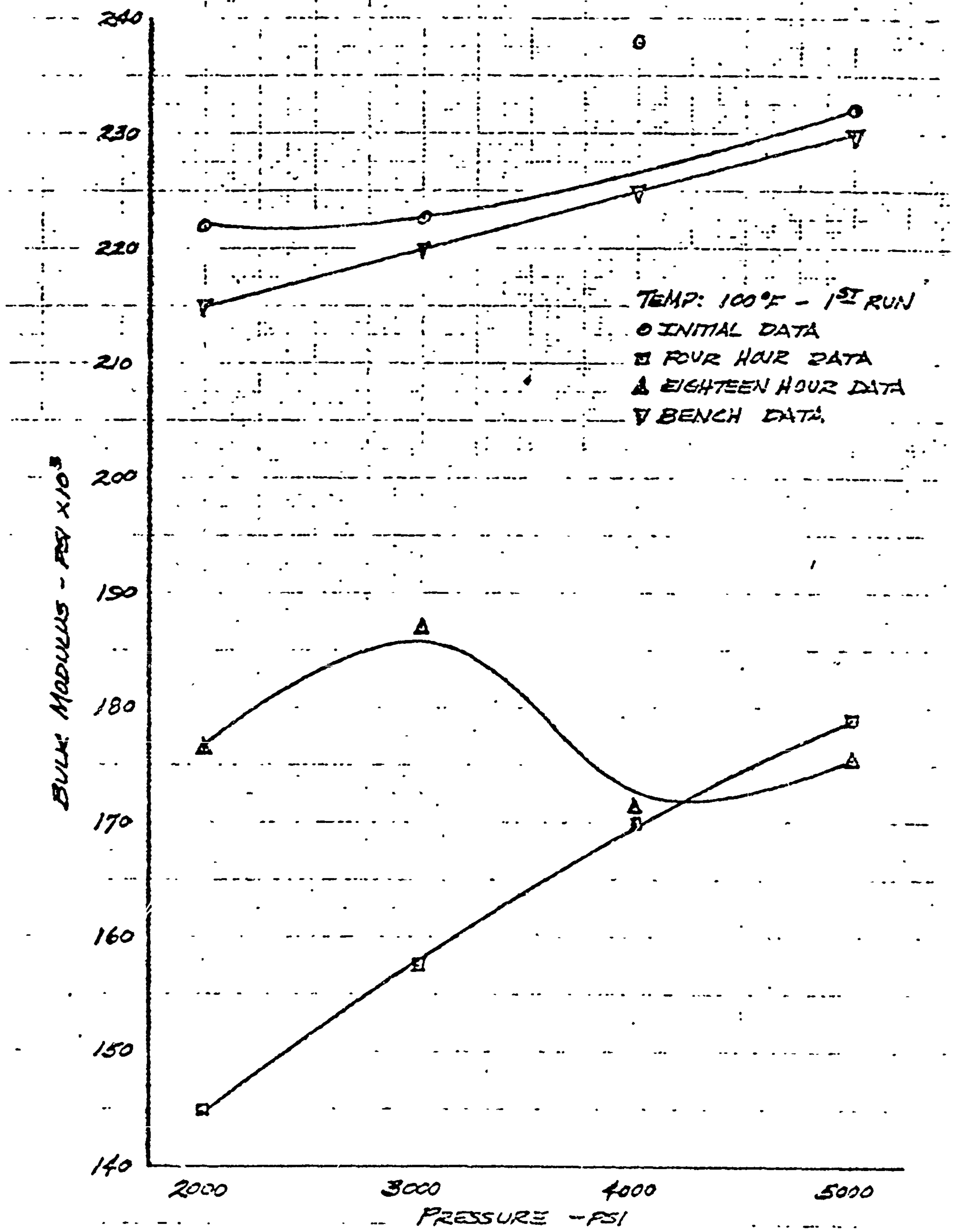

CALC			REVISED	DATE	BULK MODULUS DATA	FIG 16
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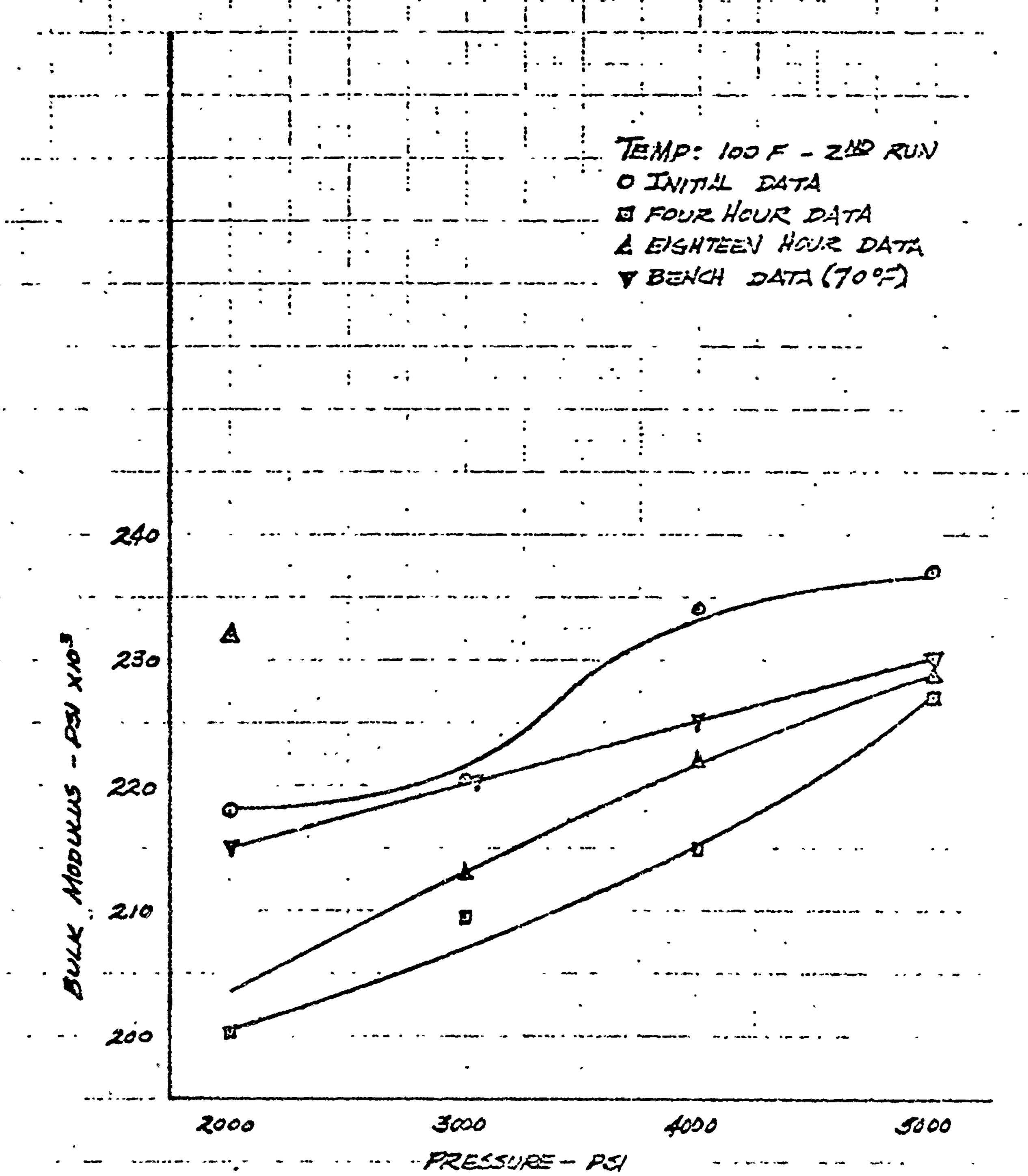

CALC			REVISED	DATE	BULK MODULUS DATA	FIG 17
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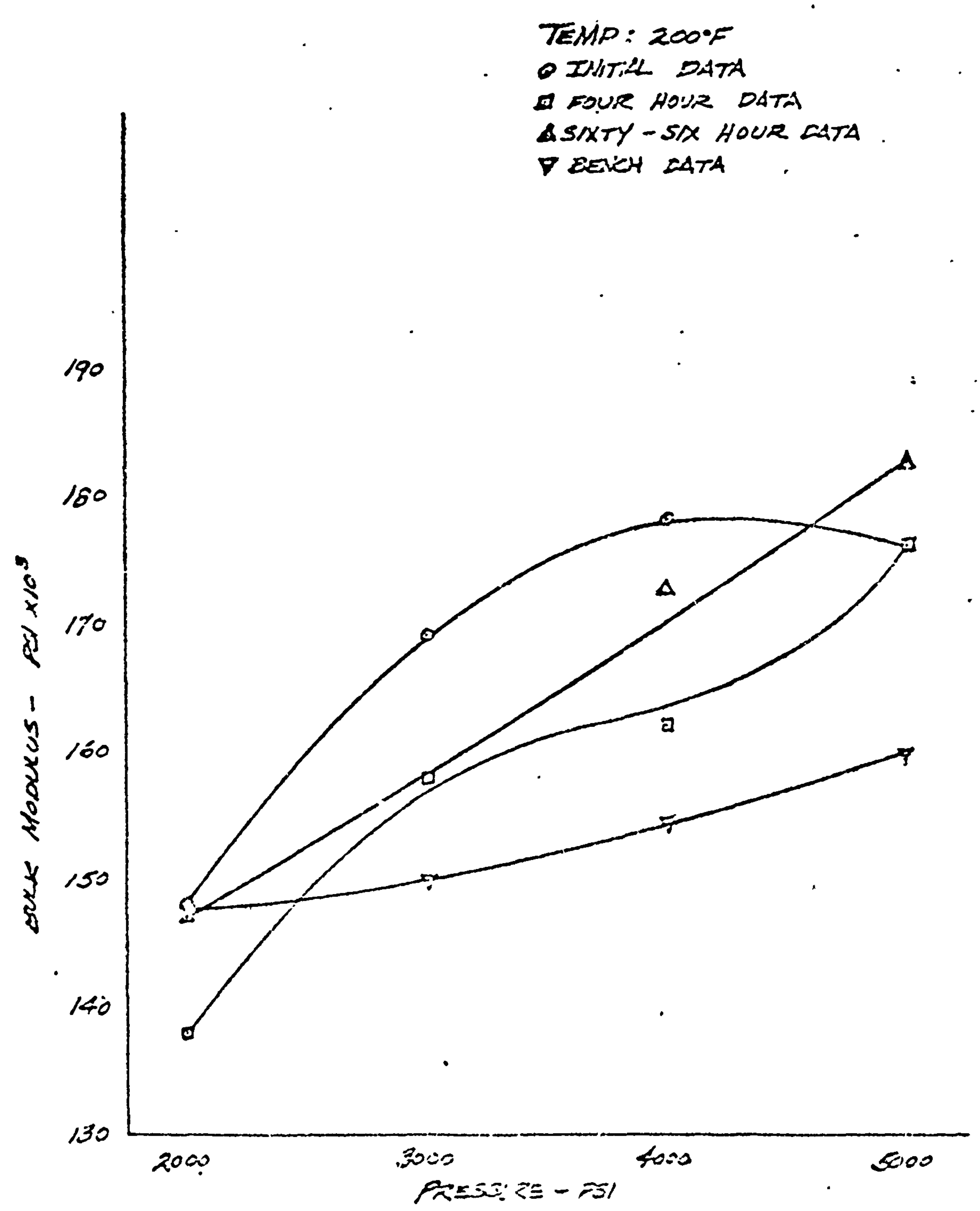

BULK MODULUS DATA
SYSTEM - MIL-H-5606B

FIG 18

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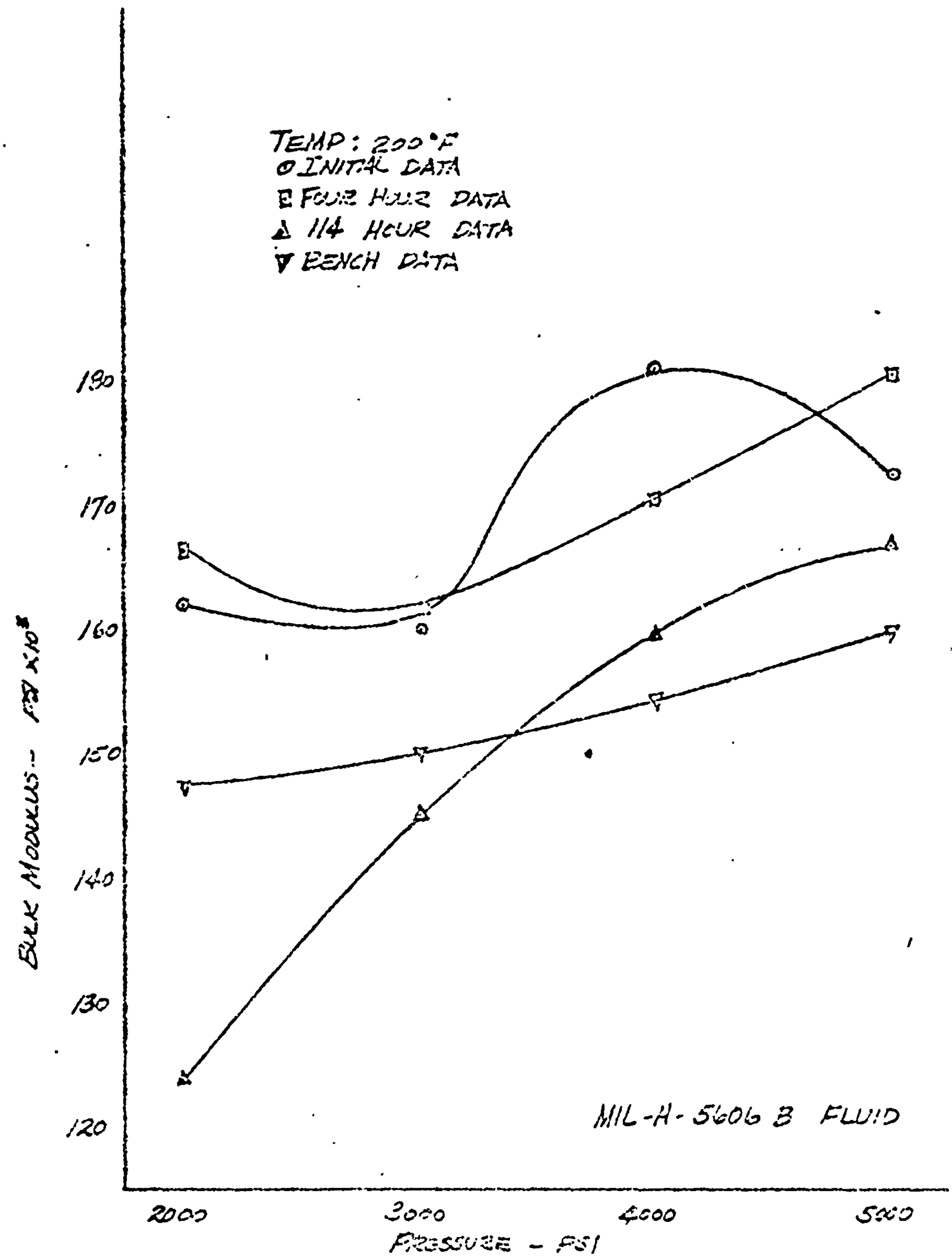

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BULK MODULUS DATA

7-HOUR EXTENDED CYCLING

FIG 19

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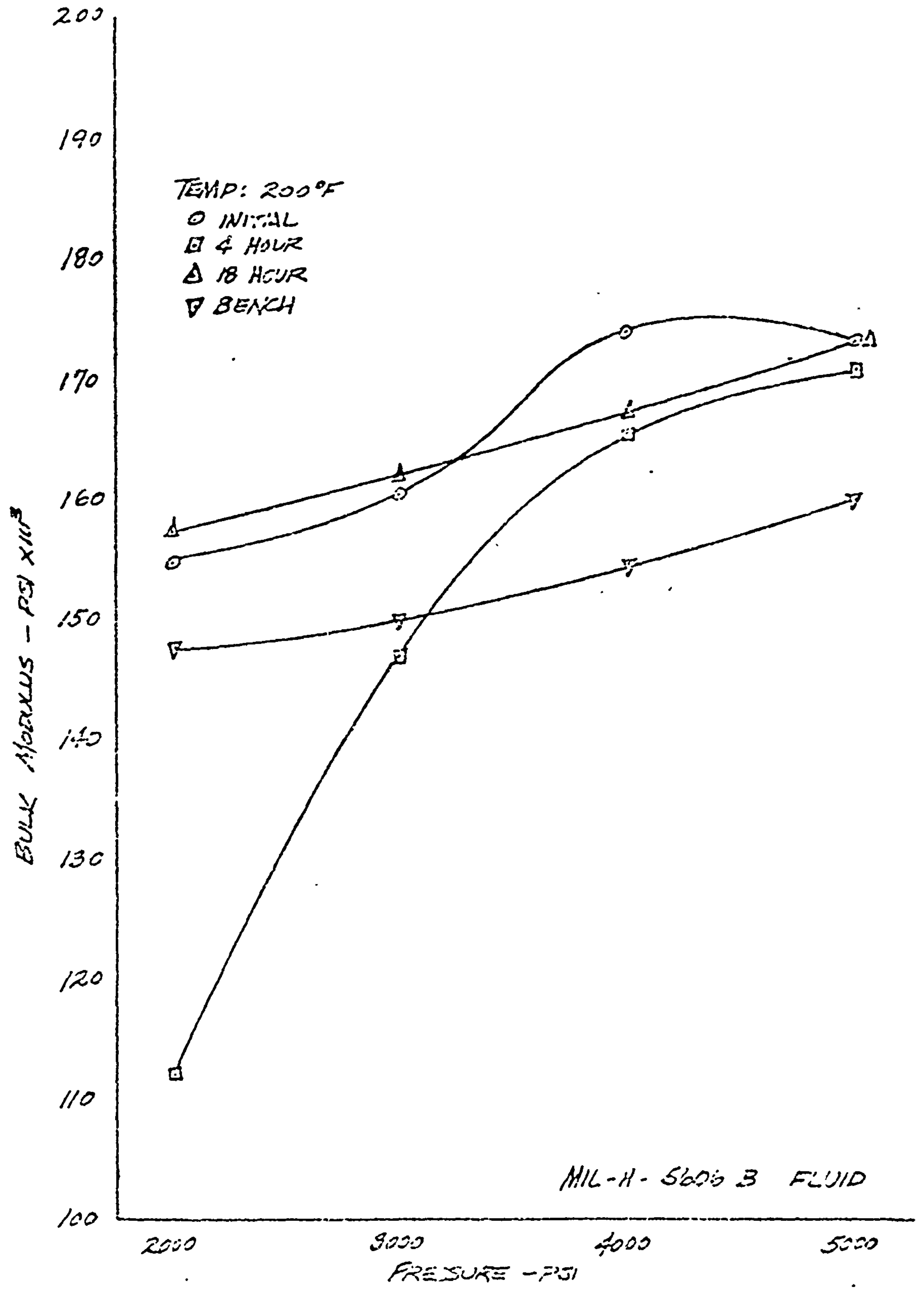

BULK MODULUS DATA

14 HOUR EXTENDED CYCLING

FIG 20

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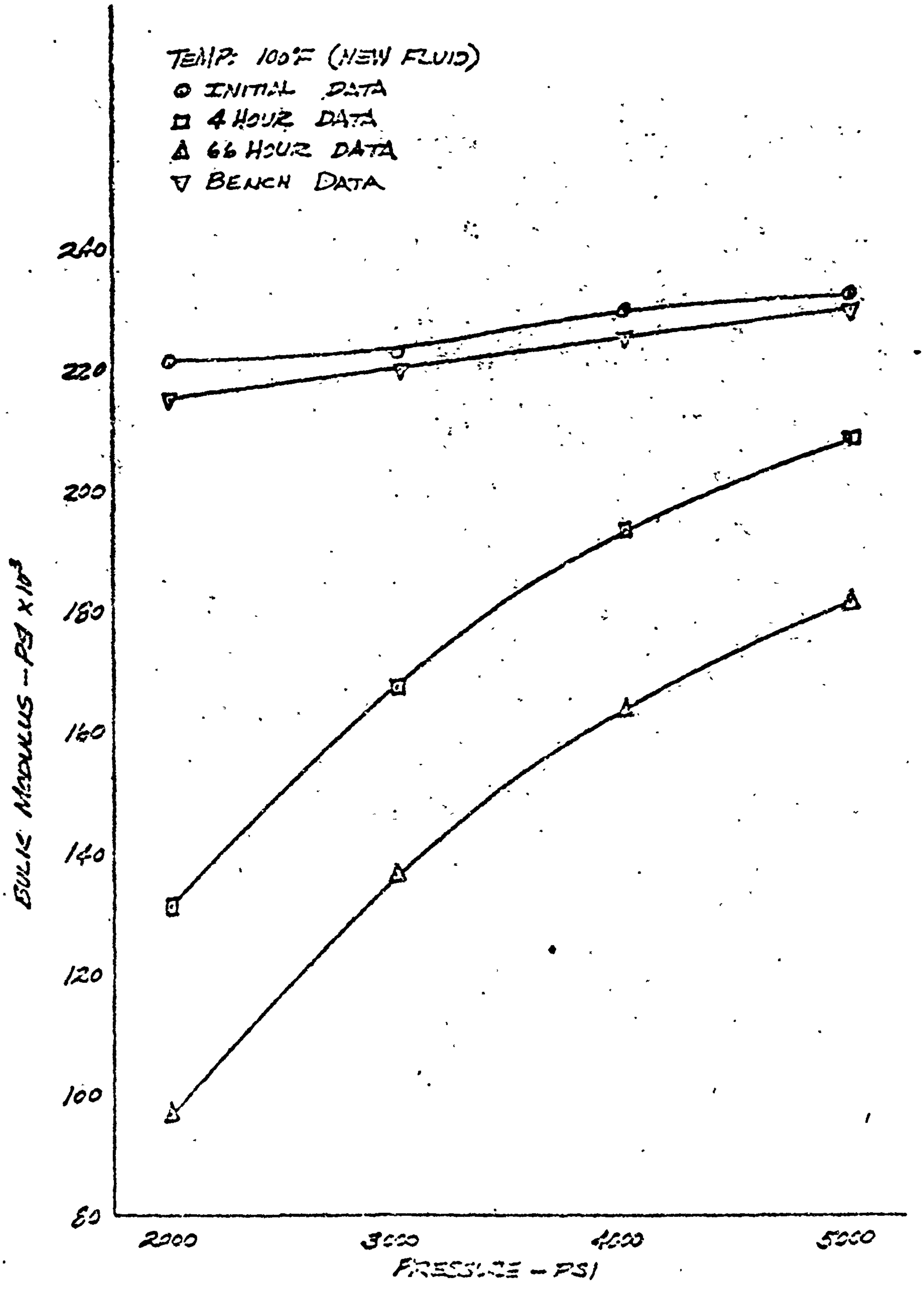

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			SYSTEM - MIL-H-5606B	D6-58362TN
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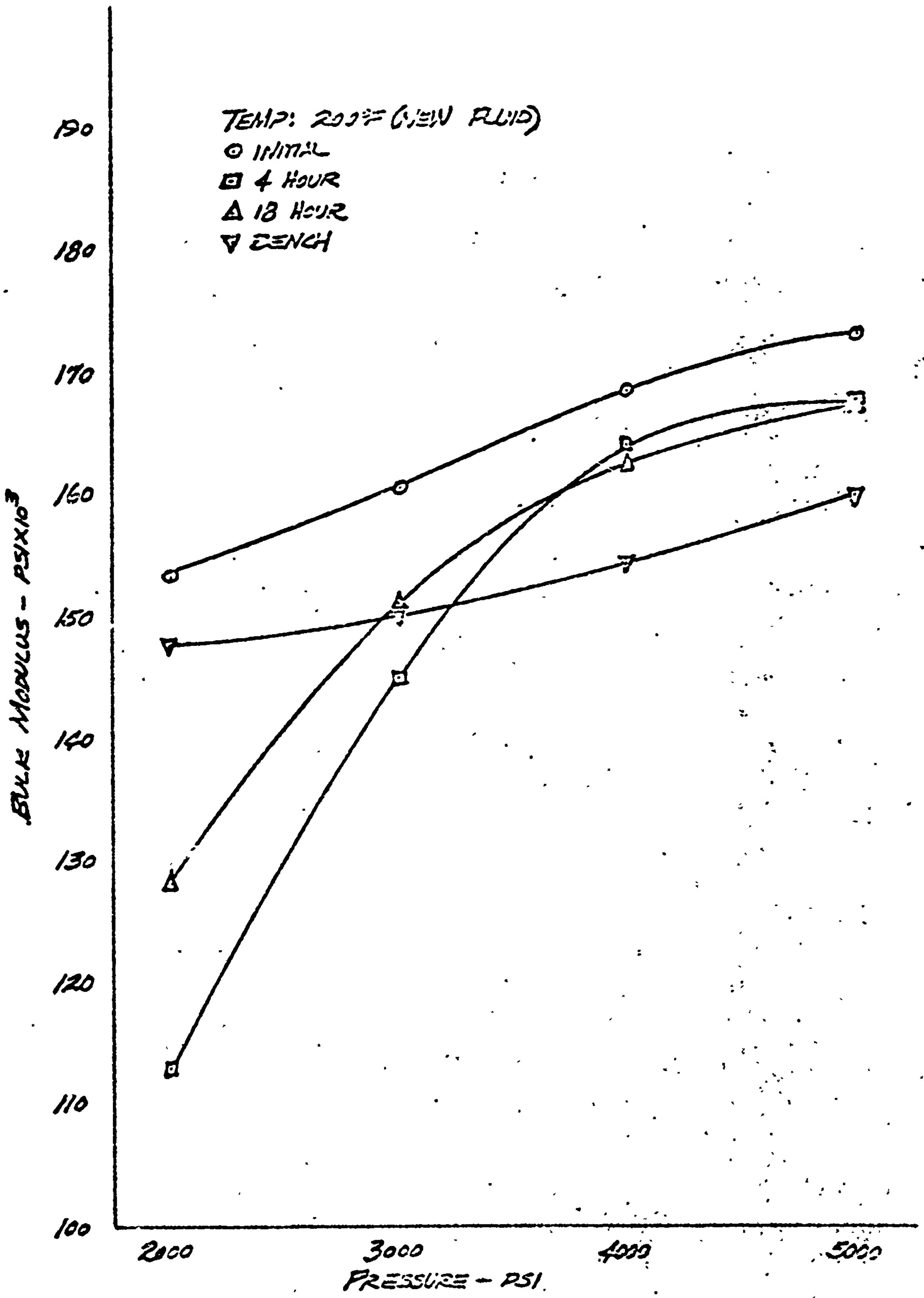

CALC			REVISED	DATE	BULK MODULUS DATA	FIG 22
CHECK					SYSTEM - MIL-H-5606B	D6-58362TN
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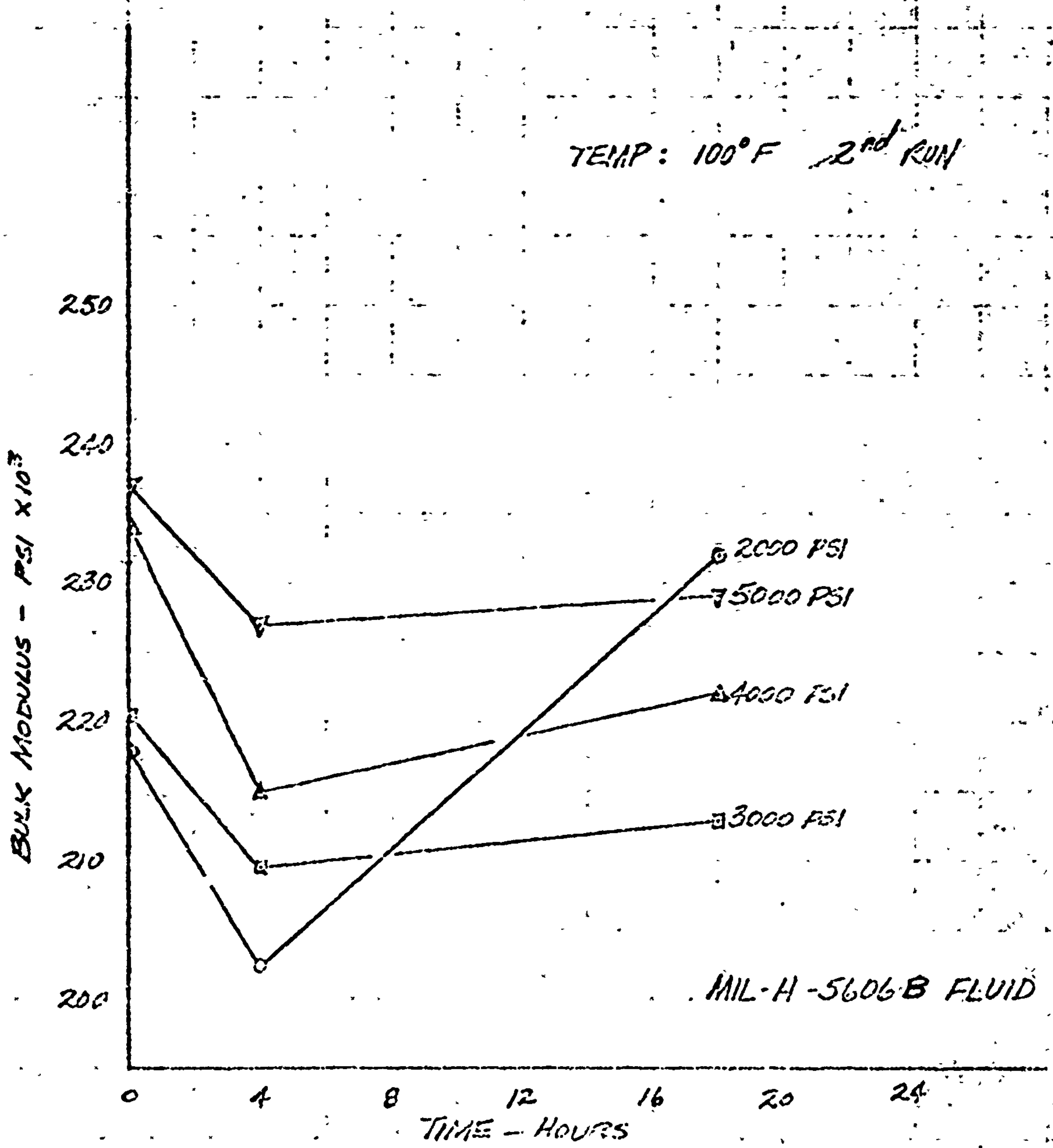
only slightly when expressed as $\Delta V/V$. At the maximum pressure, a maximum ΔV from the bench of 36 cc with an initial volume of 1136 cc yields a $\Delta V/V$ of 3.17. A similar ΔV of 11.7 cc from the system with an initial volume of 396 cc yielded a $\Delta V/V$ of 2.96. Although the data taken exhibits some repeatability, particularly good when comparing initial with initial, etc., an explanation for the variance with time is not apparent (Figures 23 through 28). One possibility is that air comes out of solution during the dormant periods causing the bulk modulus to decrease. With subsequent pressurizations (0-2000 psi initially) the air is again dissolved in the fluid and the bulk modulus increases. This might explain the results obtained after four hours but is discounted by the 18 to 114 hour data. It may also explain the increase in slope obtained with 4 hour and 18 to 114 hour data. Observance of this trend in initial test results led to the inclusion of the 100 psi pressurization in later WSX-6835 and Skydrol 500A tests.

The bench data obtained with WSX-6385 fluid was compared with published data for ETC-5251 (Figures 29 and 30). These two fluids are very similar so the accuracy obtained was deemed sufficient. The deviation between the bench and published data reached a maximum of 3.5 percent at 100 F and of 7 percent at 350 F (Figure 31).

The system data for WSX-6385 exhibited a slightly different trend than the MIL-H-5606B data. The initial values were the highest, with the 4 and 18 hour data following in decreasing order (Figures 32 and 33). This data was for zero section pressure during the dormant periods. With a pressure of 100 psi on the test section during the dormant periods, the bulk modulus measurements yielded data that was



CALC.			REVISED	DATE	VARIATION OF BULK MODULUS WITH TIME	FIG 23
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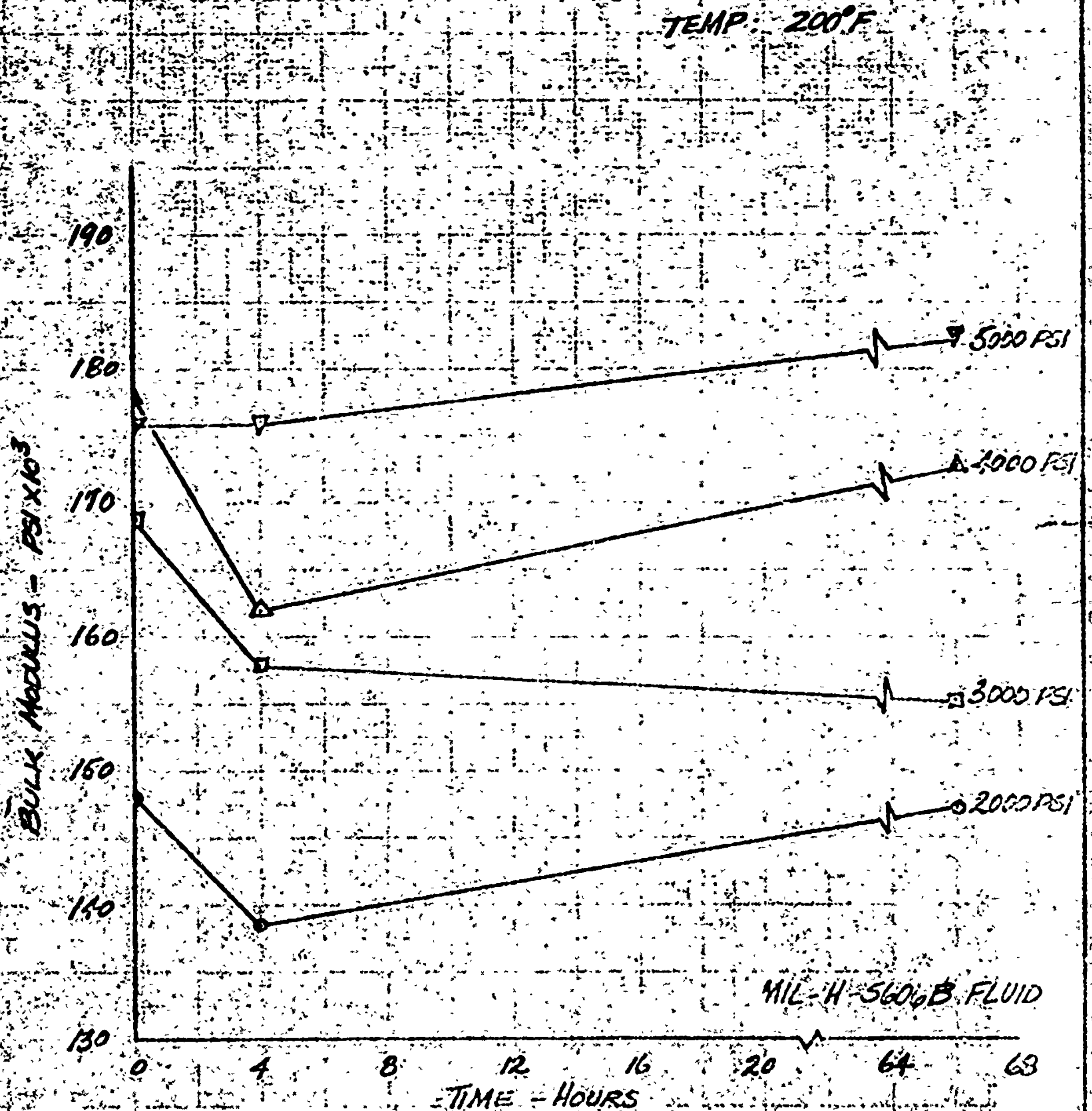

CALC			REVISED	DATE	VARIATION OF BULK MODULUS WITH TIME	FIG 24
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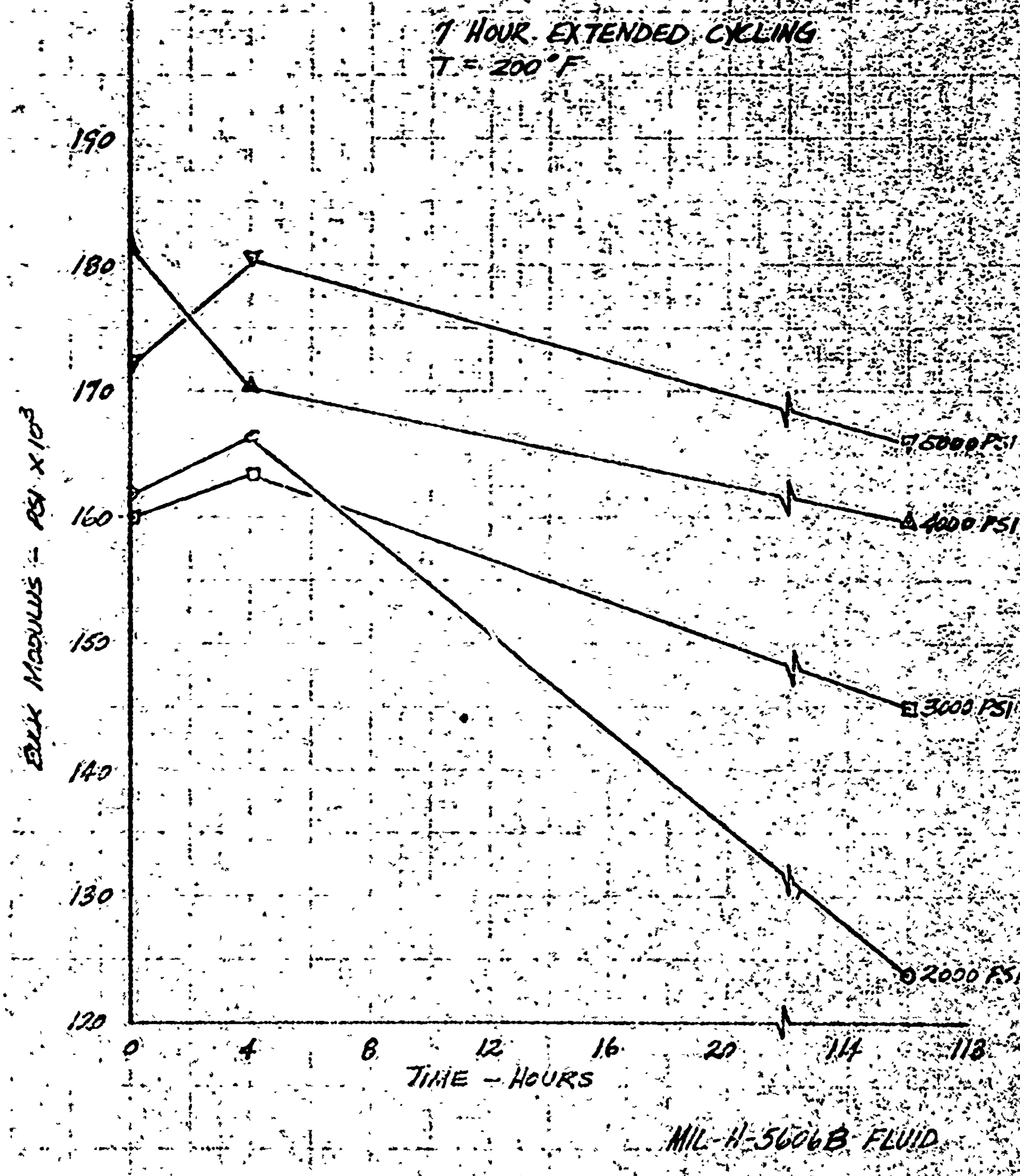

CALC			REVISED	DATE	VARIATION OF BULK MODULUS WITH TIME	FIG 25
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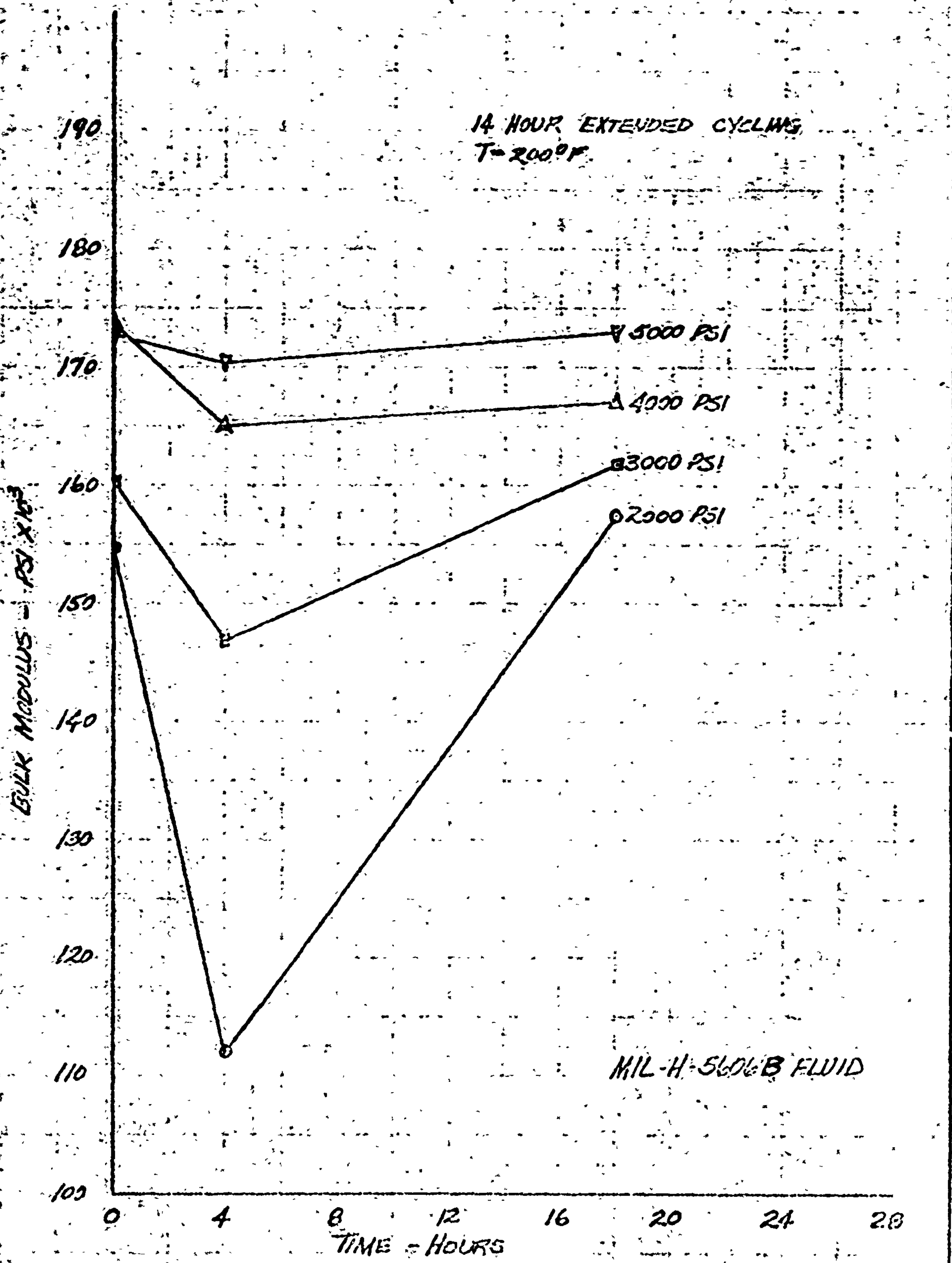

CALC			REVISED	DATE	VARIATION OF BULK MODULUS WITH TIME	FIG 26 D6-58362TN
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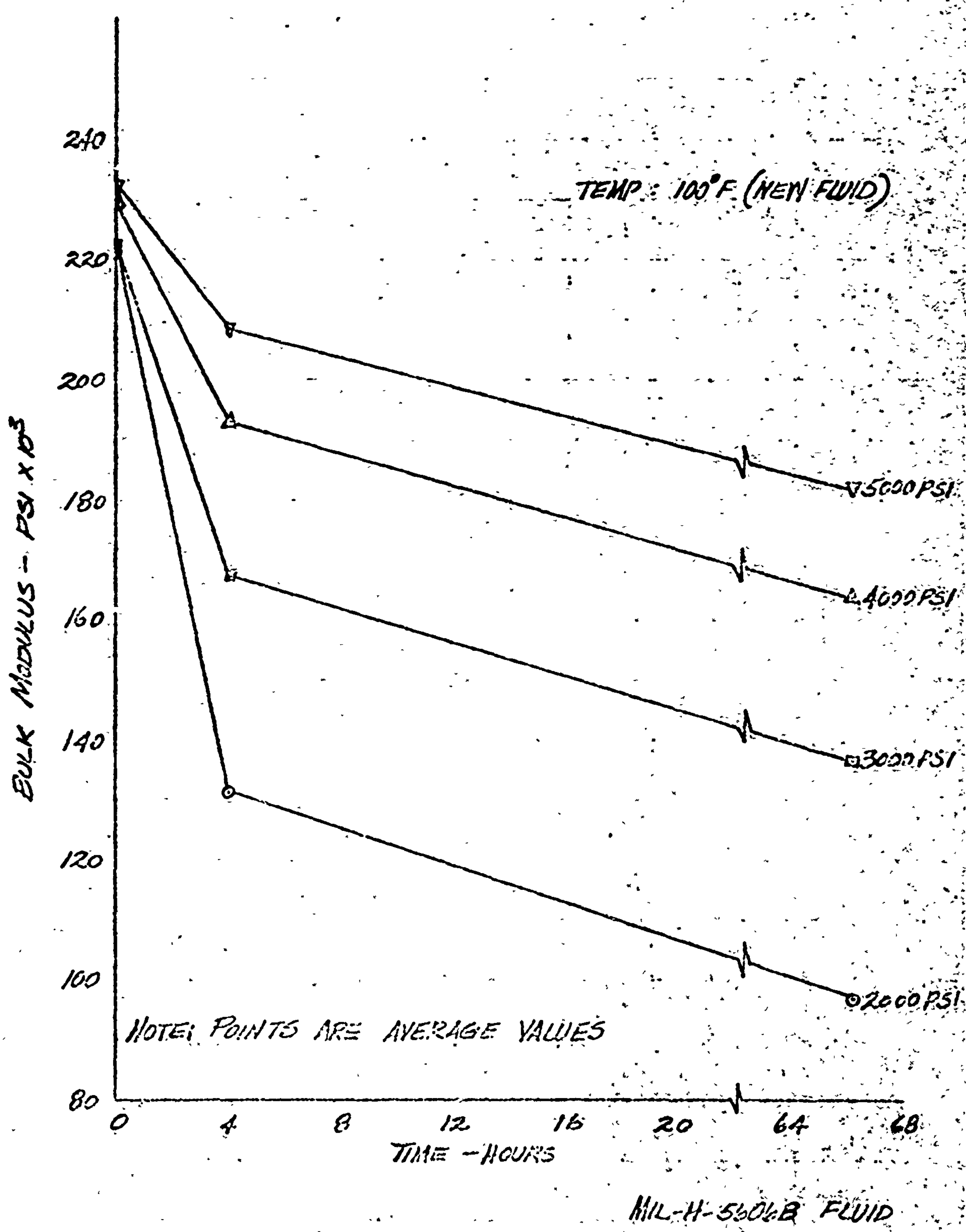

CALC			REVISED	DATE	VARIATION OF BULK MODULUS WITH TIME	FIG 27
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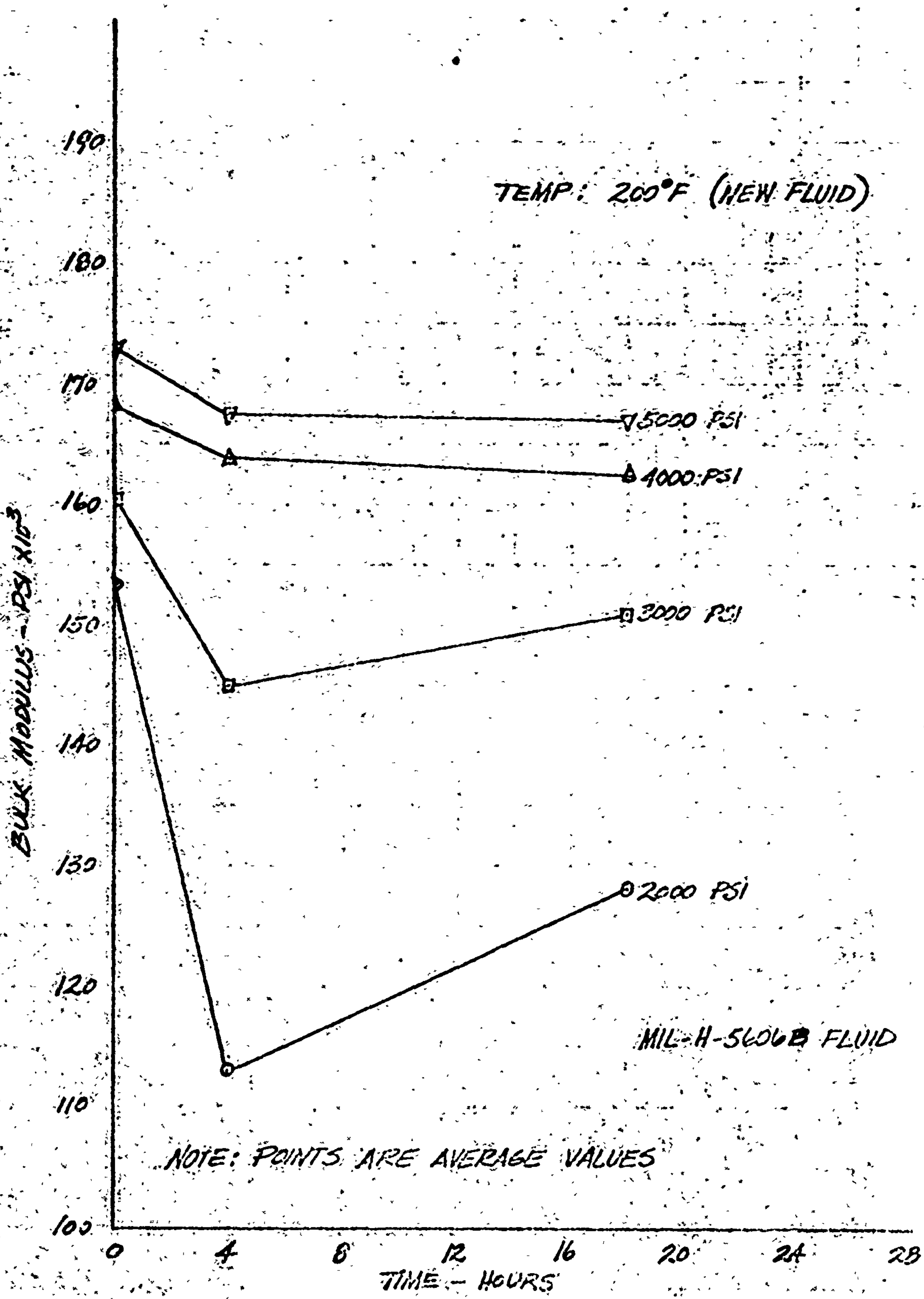

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VARIATION OF BULK MODULUS WITH TIME

FIG 28

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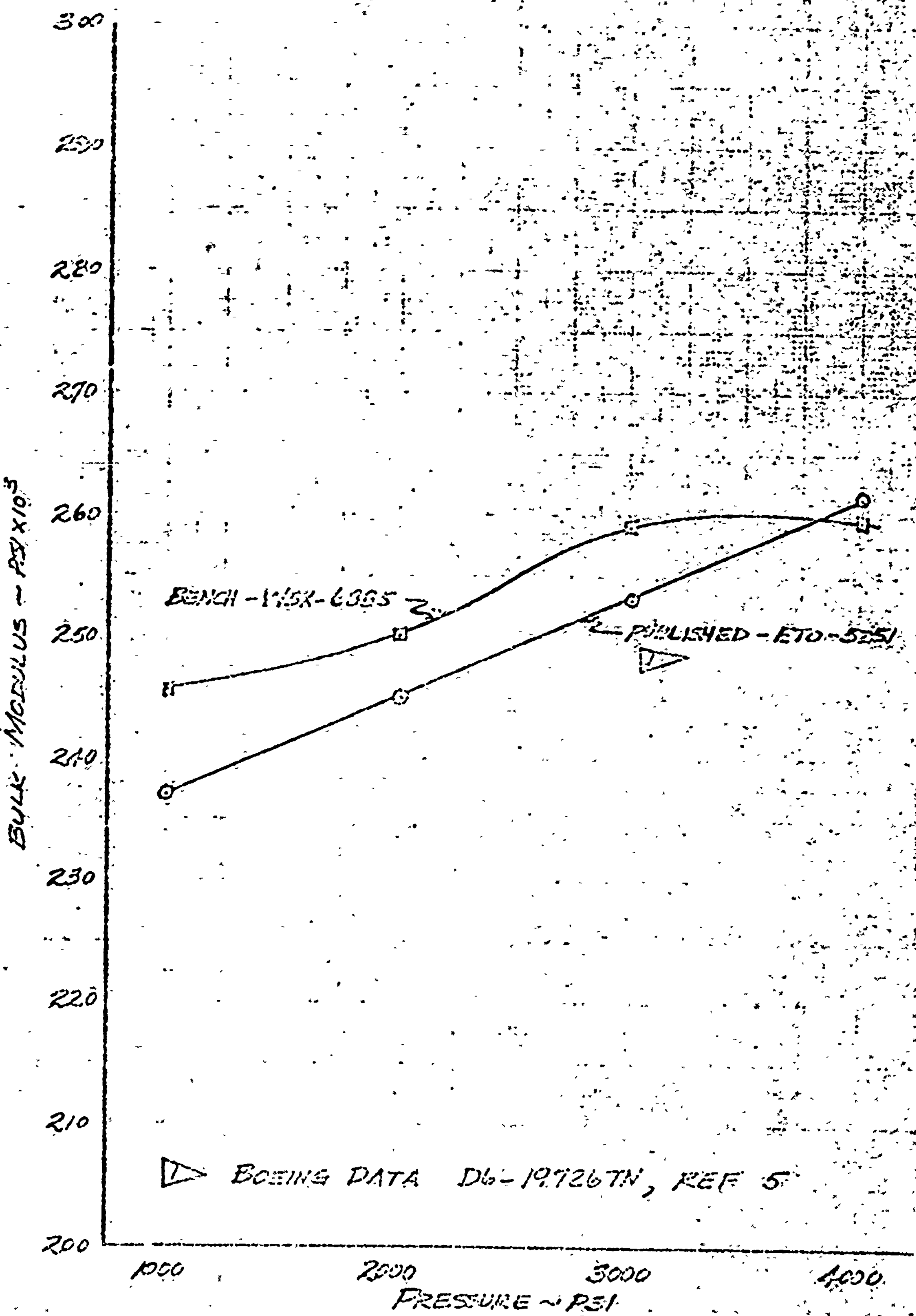
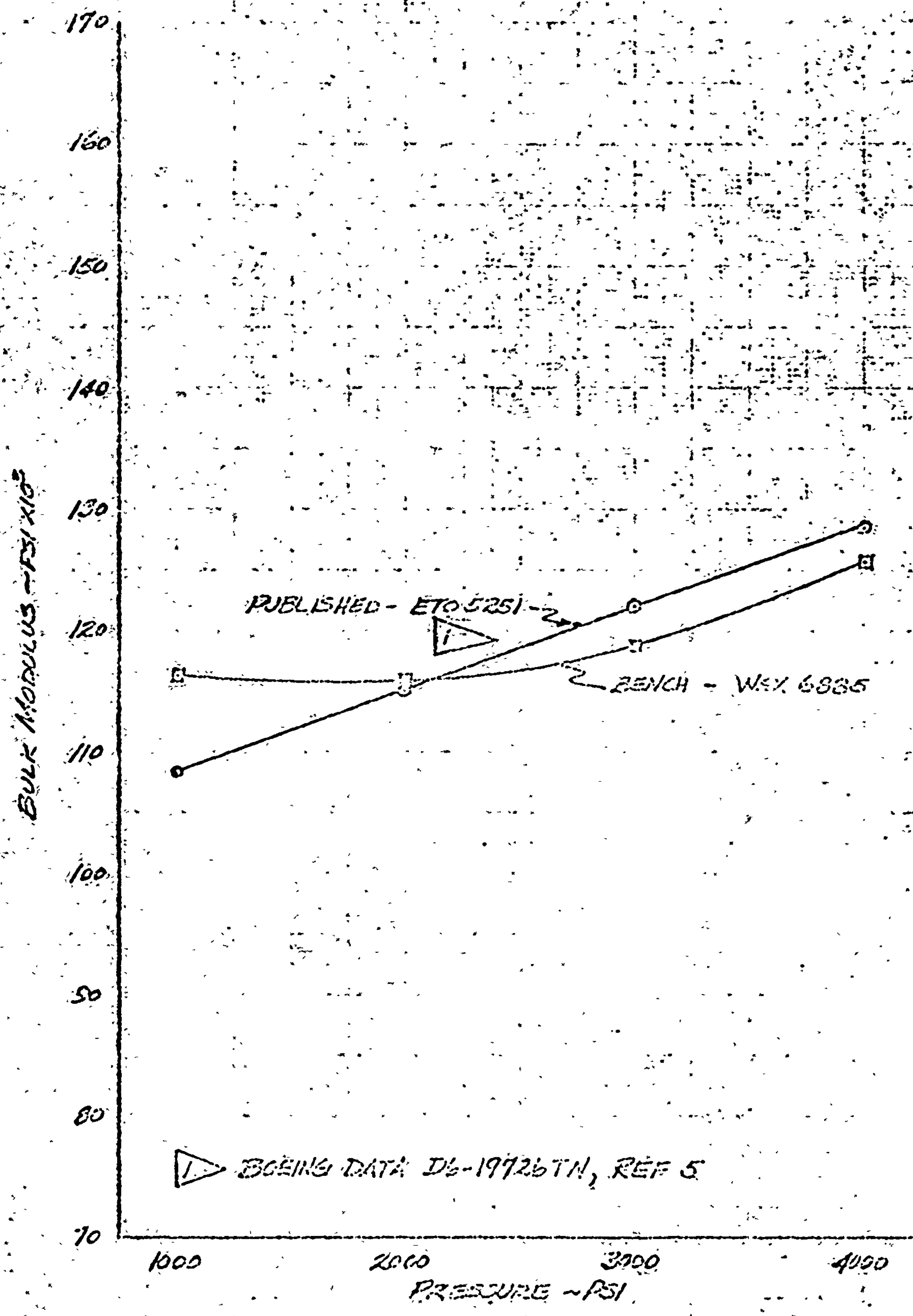
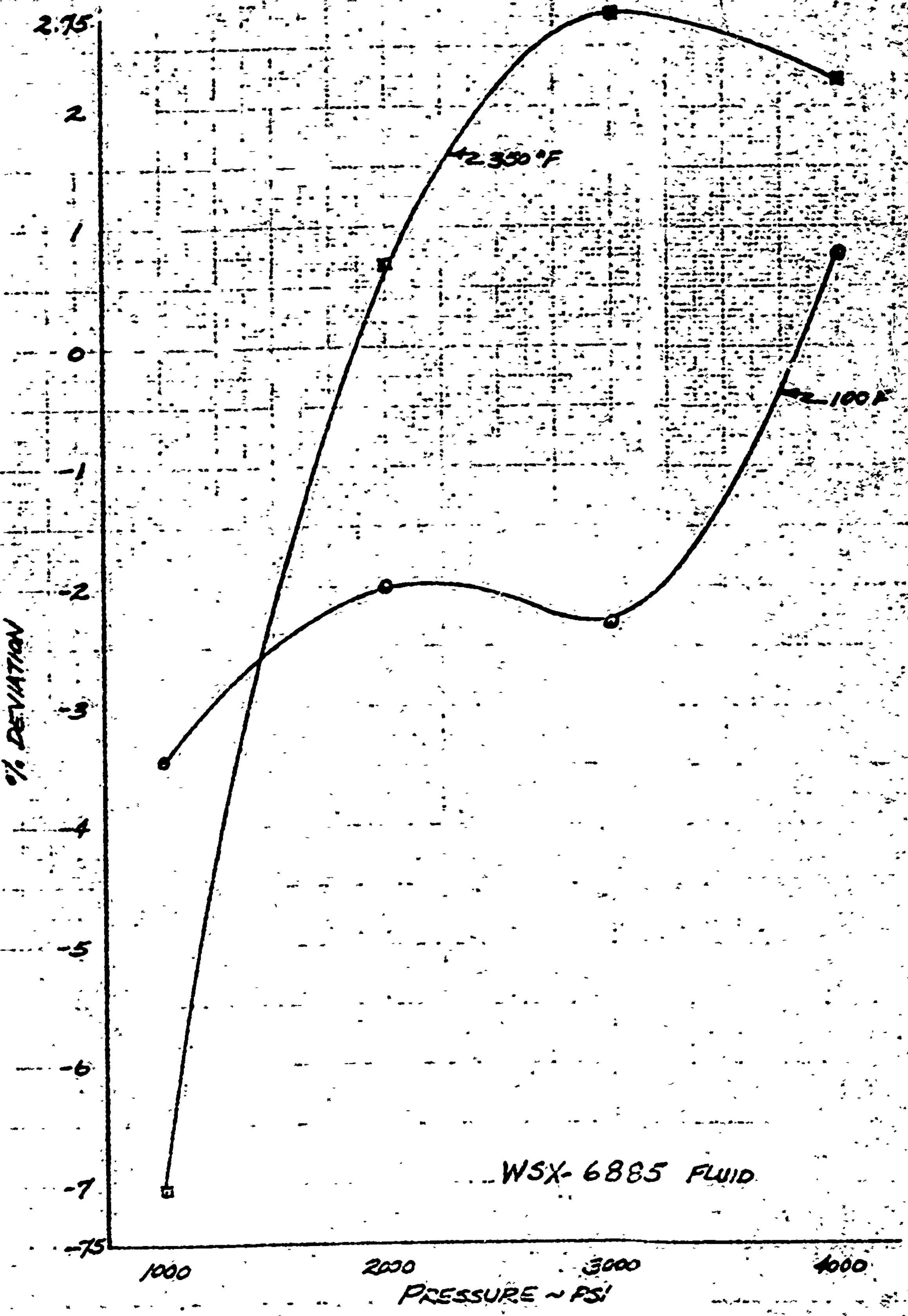


CALC			REVISED	DATE	COMPARISON OF BENCH AND PUBLISHED DATA ~ 100°F	FIG. 29
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 43
APR						

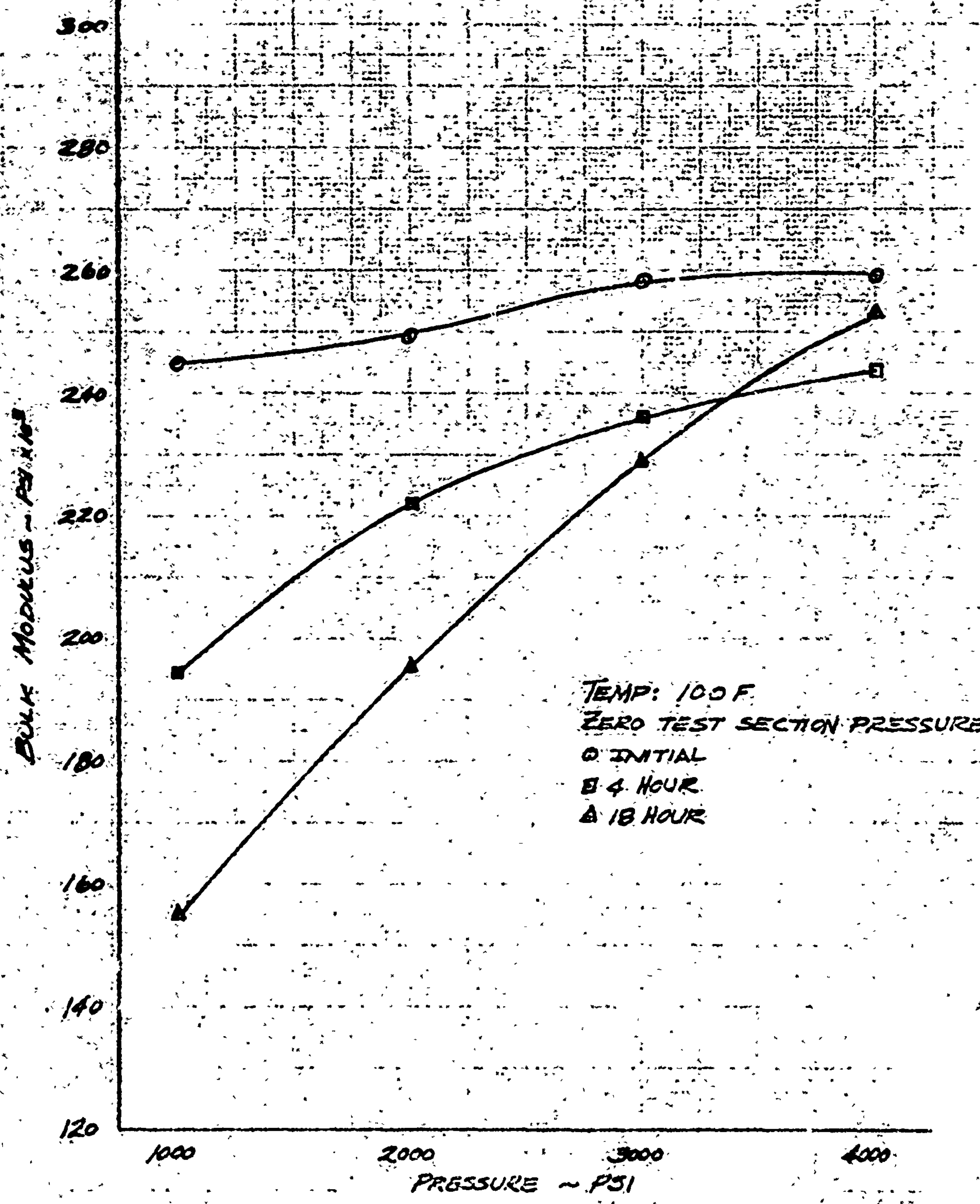


CALC			REVISED	DATE	COMPARISON OF BENCH AND PUBLISHED DATA - 350 °F	FIG. 30
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 44
APR						



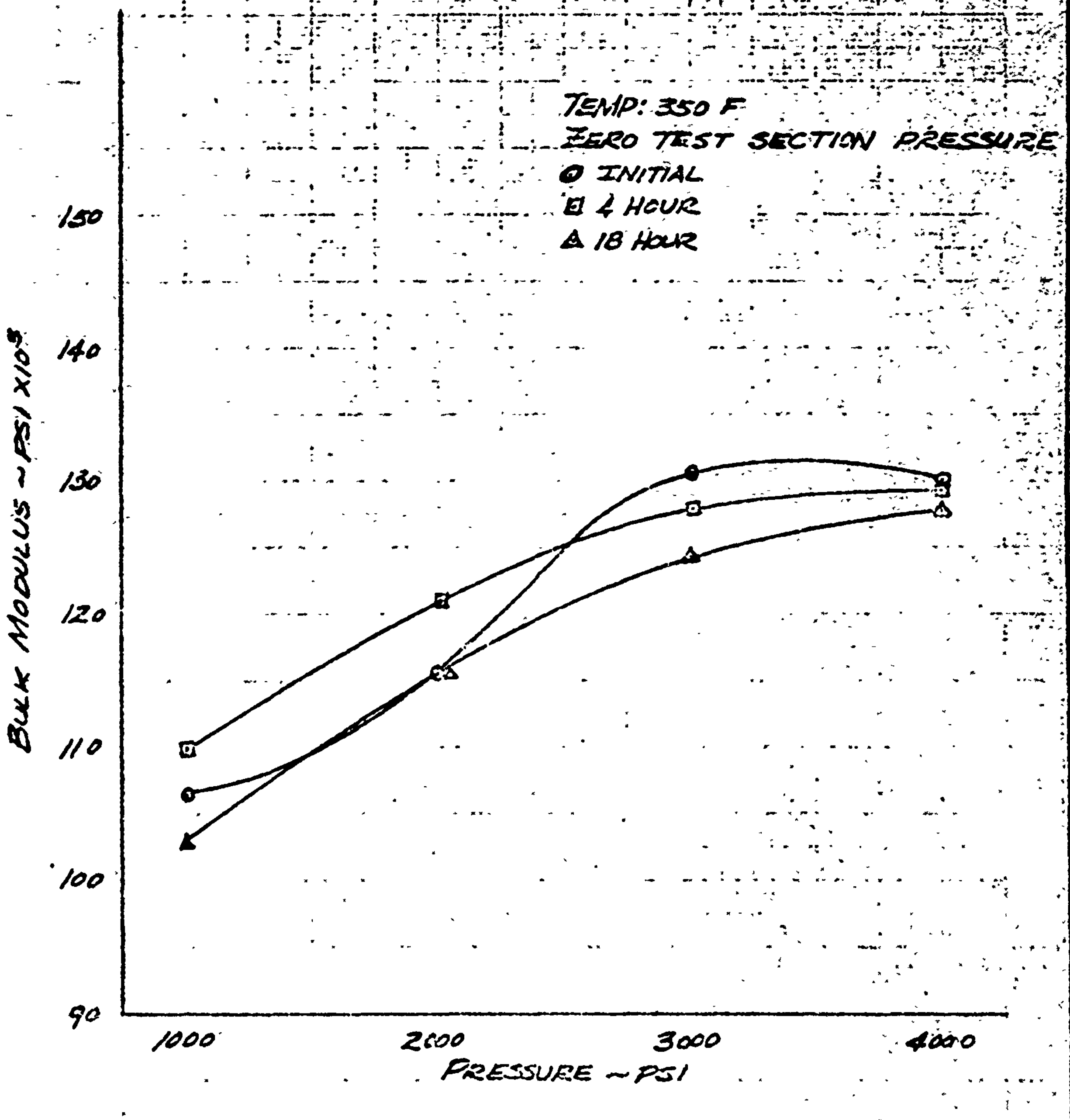
			REVISED	DATE		
CALC					DEVIATION BETWEEN BENCH AND PUBLISHED BULK MODULUS	FIG. 31
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 45
APR						

TD 461 C-R4



CALC			REVISED	DATE	BULK MODULUS DATA SYSTEM WSX-6885	FIG. 32
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 46
APR						

TD 461 C-R4



			REVISED	DATE		
CALC					BULK MODULUS DATA SYSTEM WSX-6885	FIG. 33
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 47
APR						

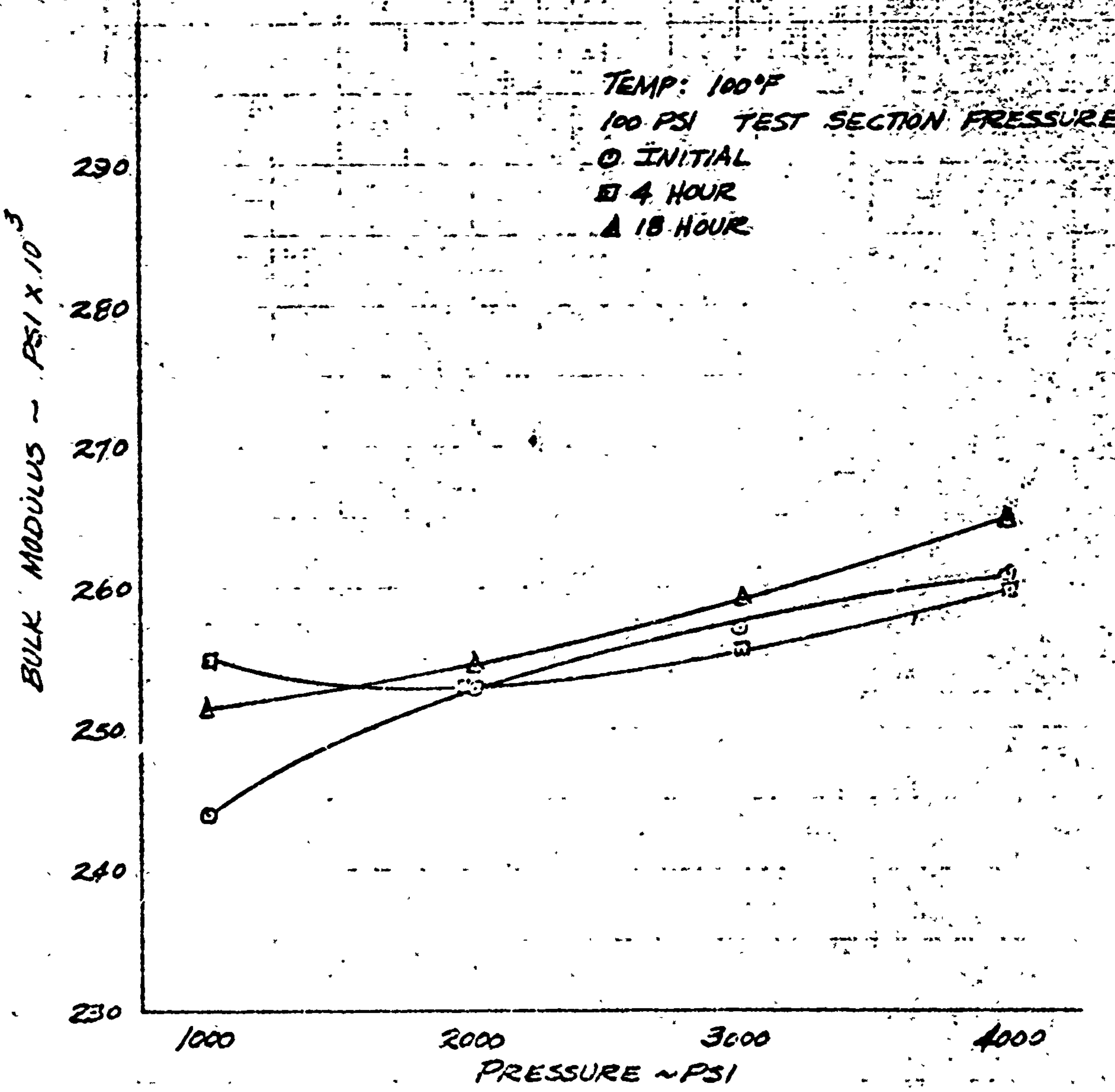
TD 461 C-R4

repeatable within test tolerances (Figures 34 and 35). A possible explanation for these results, in accordance with the reason given previously, is that the air remains in solution with the fluid due to pressure. In comparing the variation of the bulk modulus with time, the effect of pressurization during dormant periods can also be seen with the 18 hour values changing little from the initial values (Figures 36 through 41).

Fluid cycling following a four hour dormant period yielded greatly different results for each temperature. At 100 F the four hour data decreased as expected, further decreased following two cycles, and increased after two additional cycles (Figure 40). The slope of the curves also changed. At 350 F the slope of the curves changes slightly with cycling with the values remaining essentially unchanged (Figure 41).

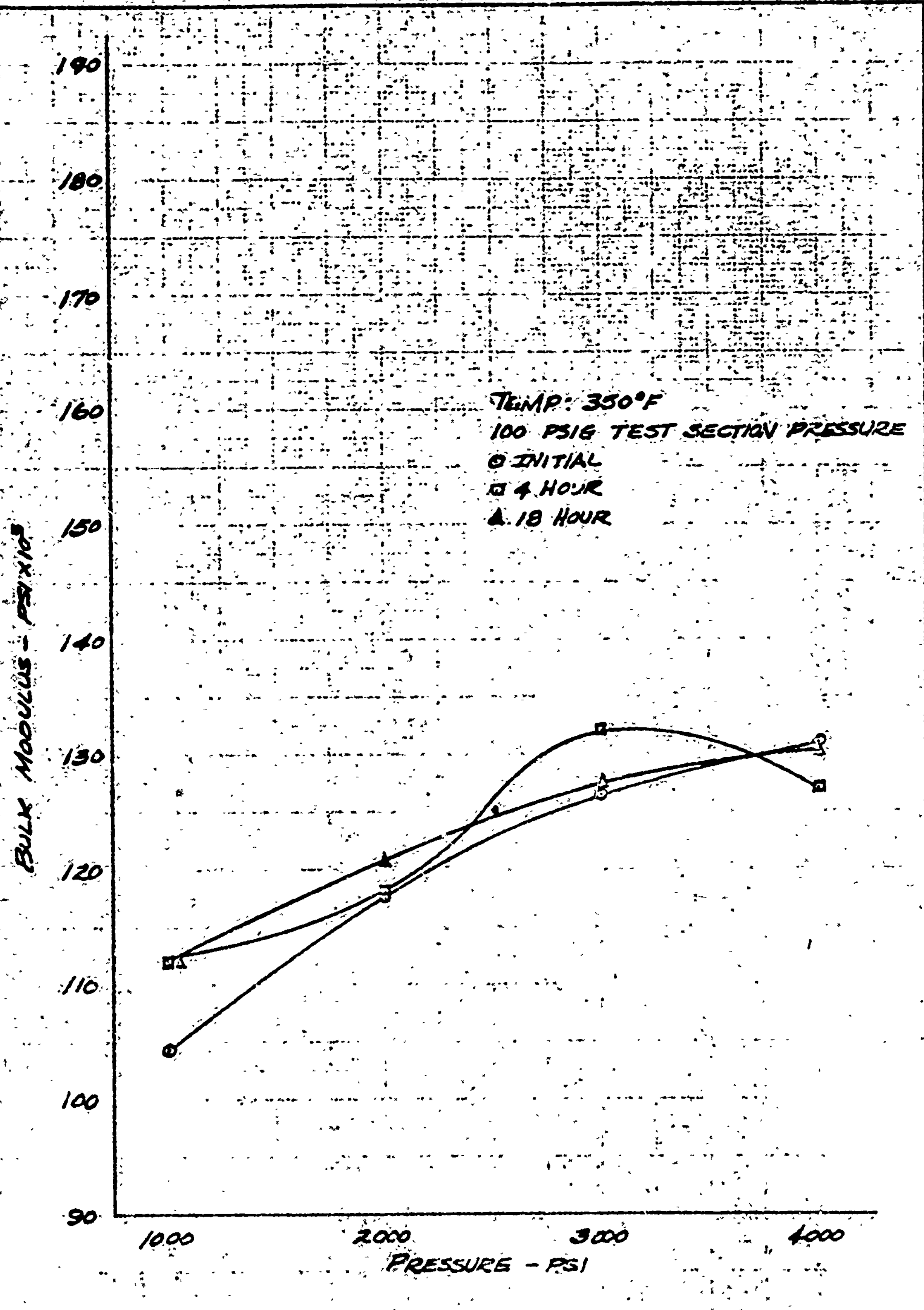
The bench data obtained with Skydrol 500A fluid was compared with published data from three sources as sufficient single source data was not available (Figures 42 and 43). This data was obtained from The Boeing Design Manual and from two separate Monsanto sources. Due to the inconsistency of this data when compared, the deviations between bench and published data were not calculated as they would be meaningless. This inconsistency is not uncommon when bulk modulus data from various sources is compared and further complicates the problem of determining the most correct value.

The system data for Skydrol 500A exhibited a trend similar to the WSX-6885 data. With zero test section pressure during the dormant periods, the initial values were the greatest followed in decreasing order

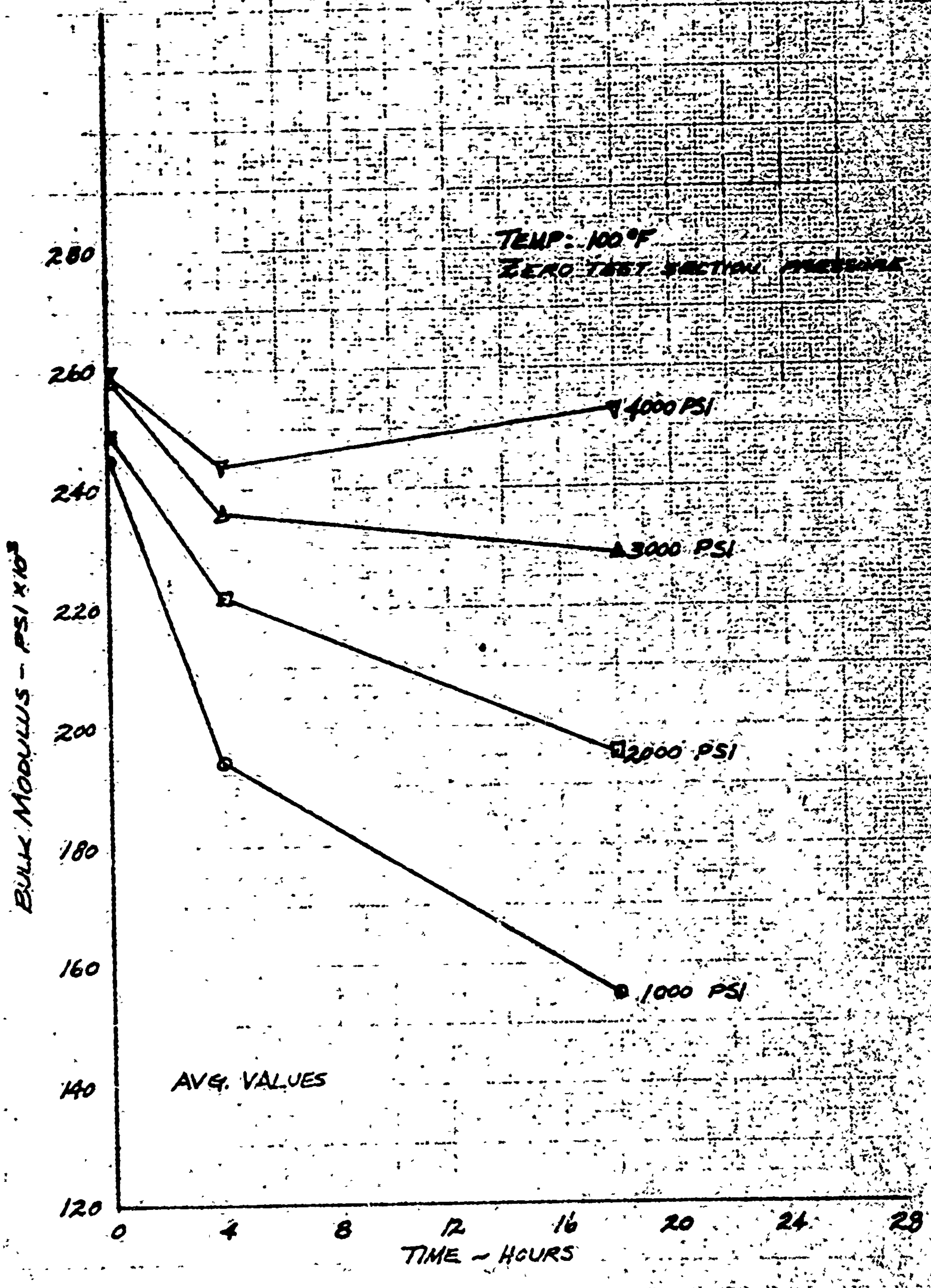


CALC			REVISED	DATE	BULK MODULUS DATA SYSTEM WSX-6835	FIG. 34
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 49
APR						

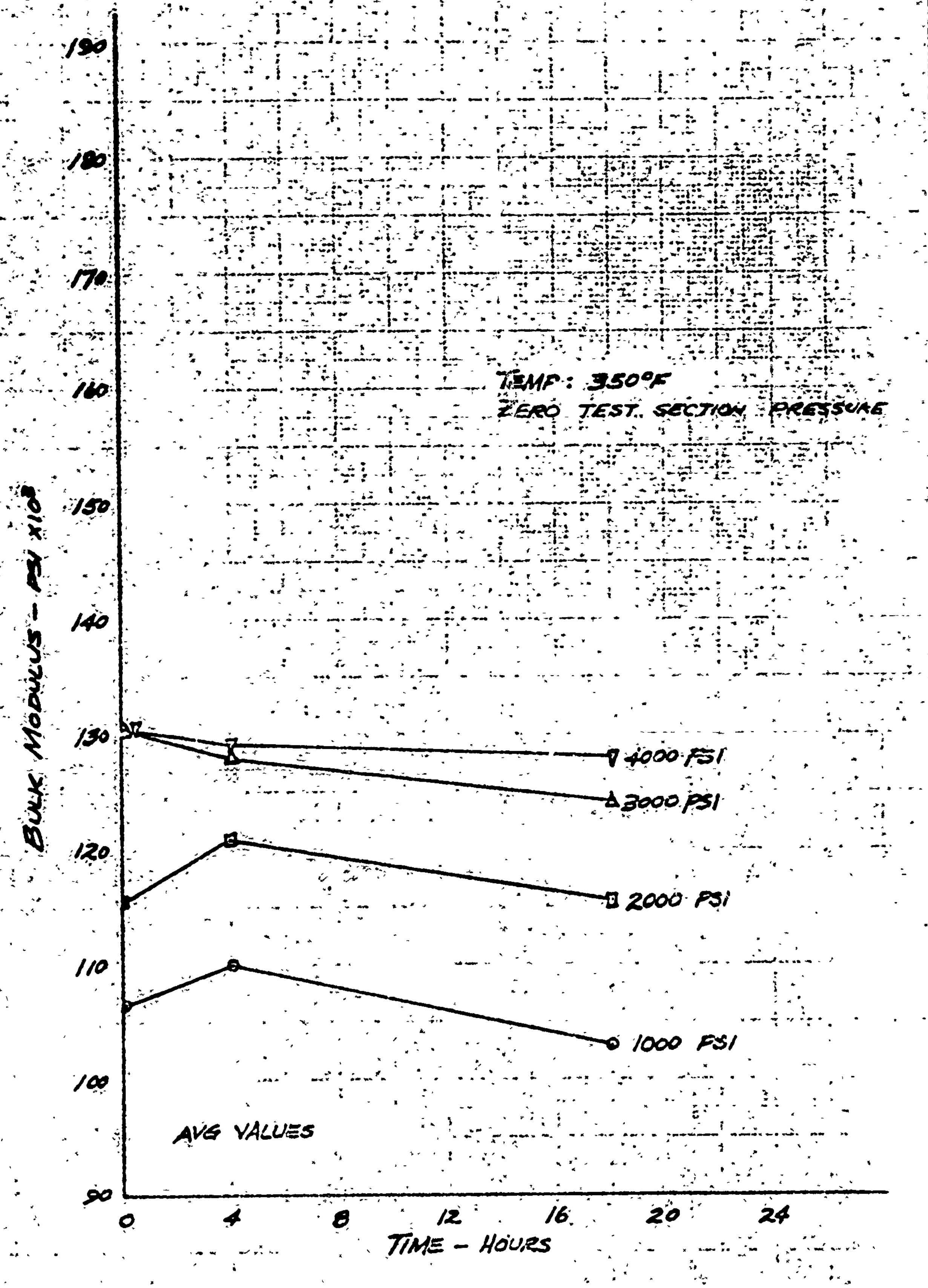
TD 461 C-R4



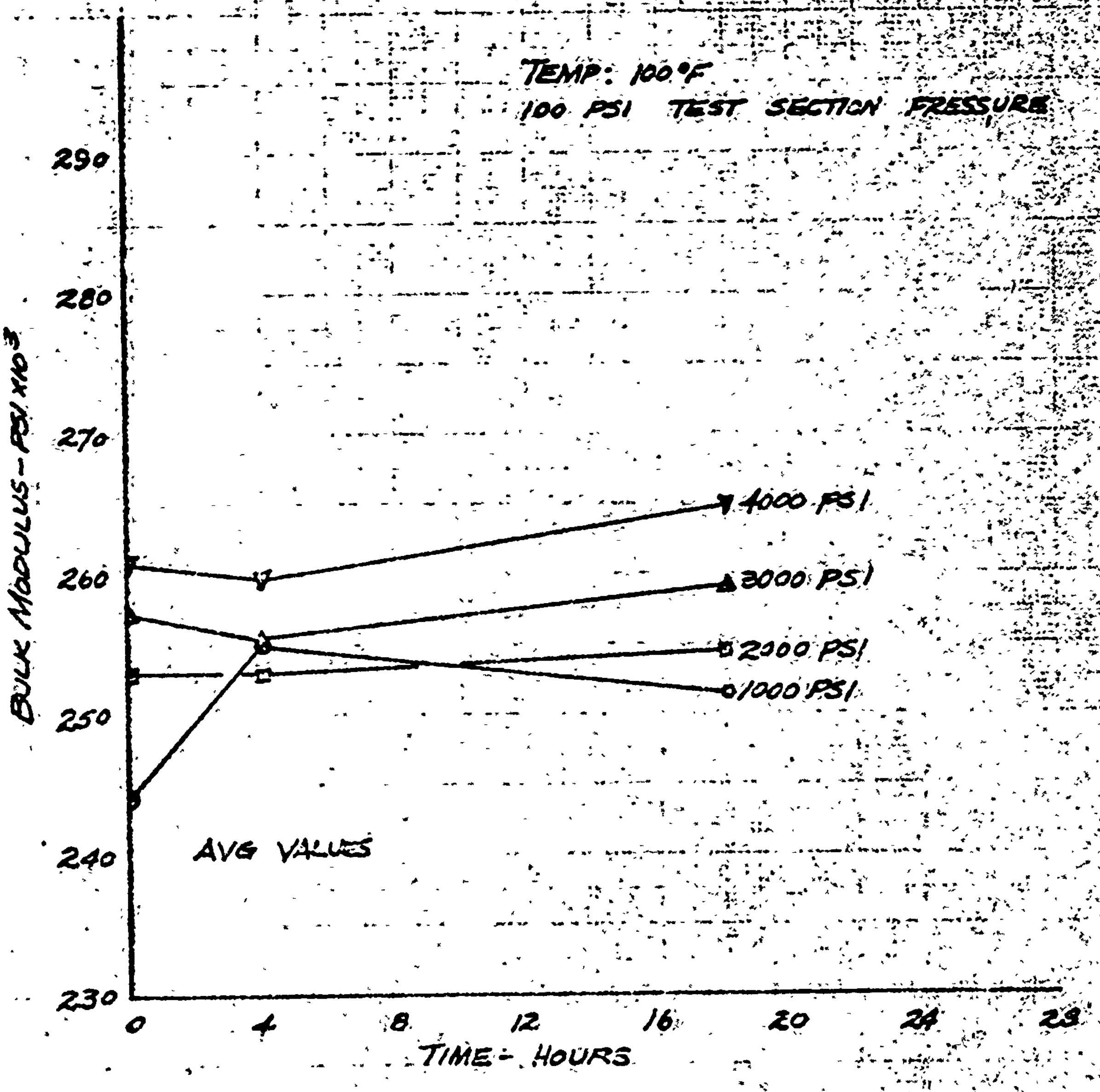
CALC			REVISED	DATE	BULK MODULUS DATA SYSTEM WSX-6885	FIG. 35
CHECK						D6-58362TN
APR						
APR					THE BOEING COMPANY	PAGE 50



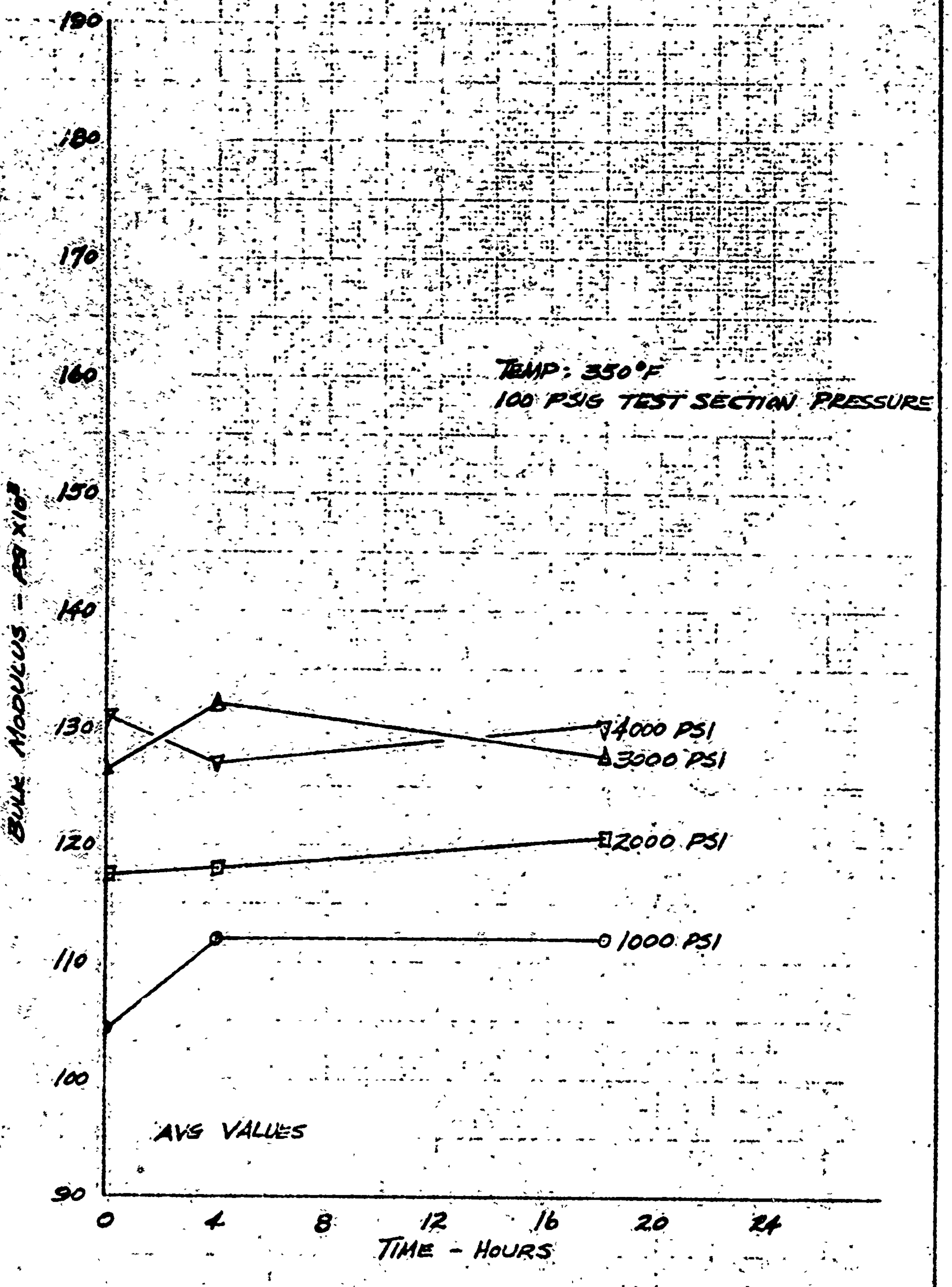
CALC			REVISED	DATE	BULK MODULUS VS. TIME SYSTEM WSX 6885	FIG. 36
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 51
APR						



CALC			REVISED	DATE	BULK MODULUS VS. TIME SYSTEM WSX-6885	FIG. 37 D6-58362TN
CHECK						
APR						
APR					THE BOEING COMPANY	PAGE 52

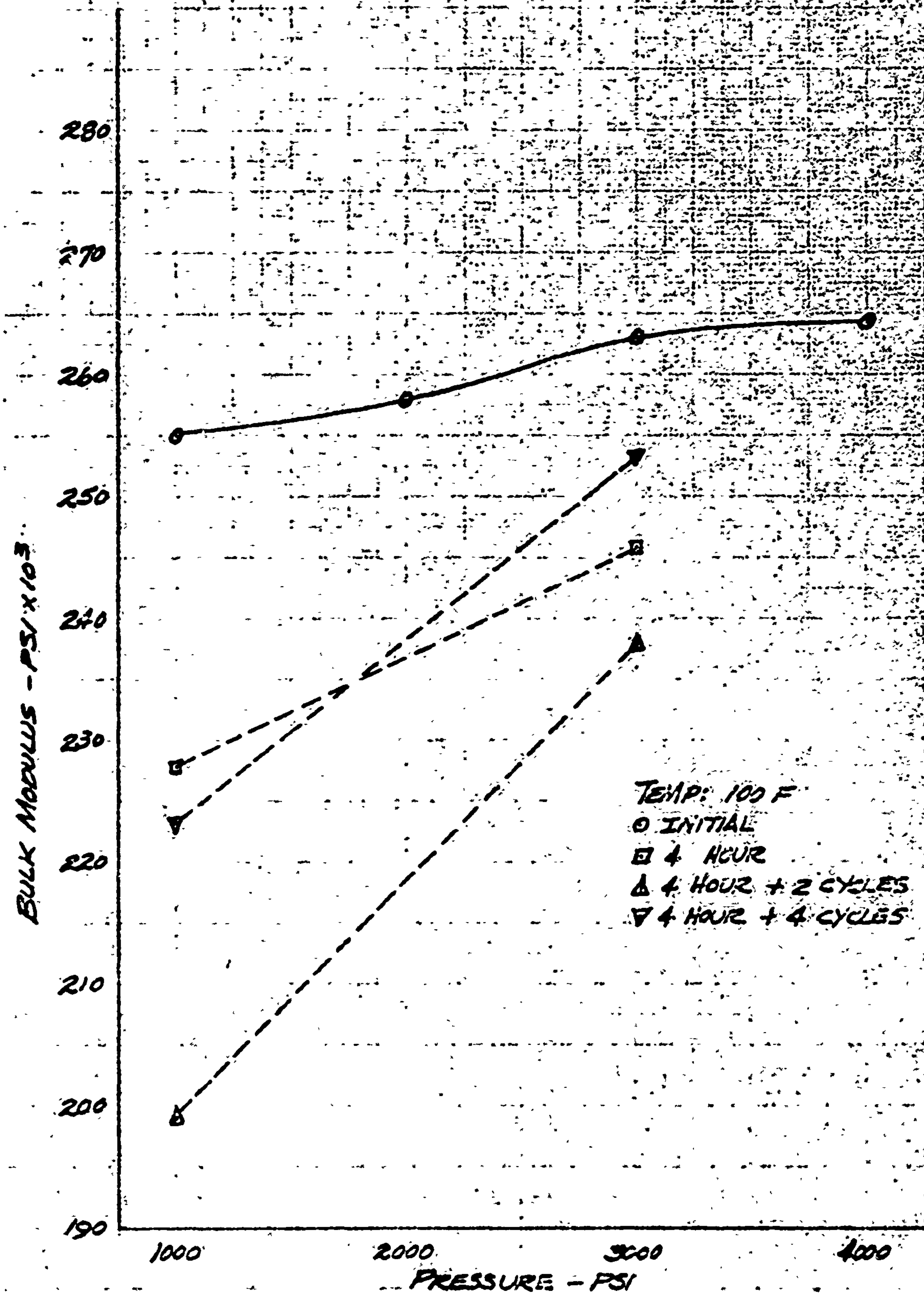


CALC			REVISED	DATE	BULK MODULUS VS. TIME SYSTEM WSX-6885	FIG. 38
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 53
APR						

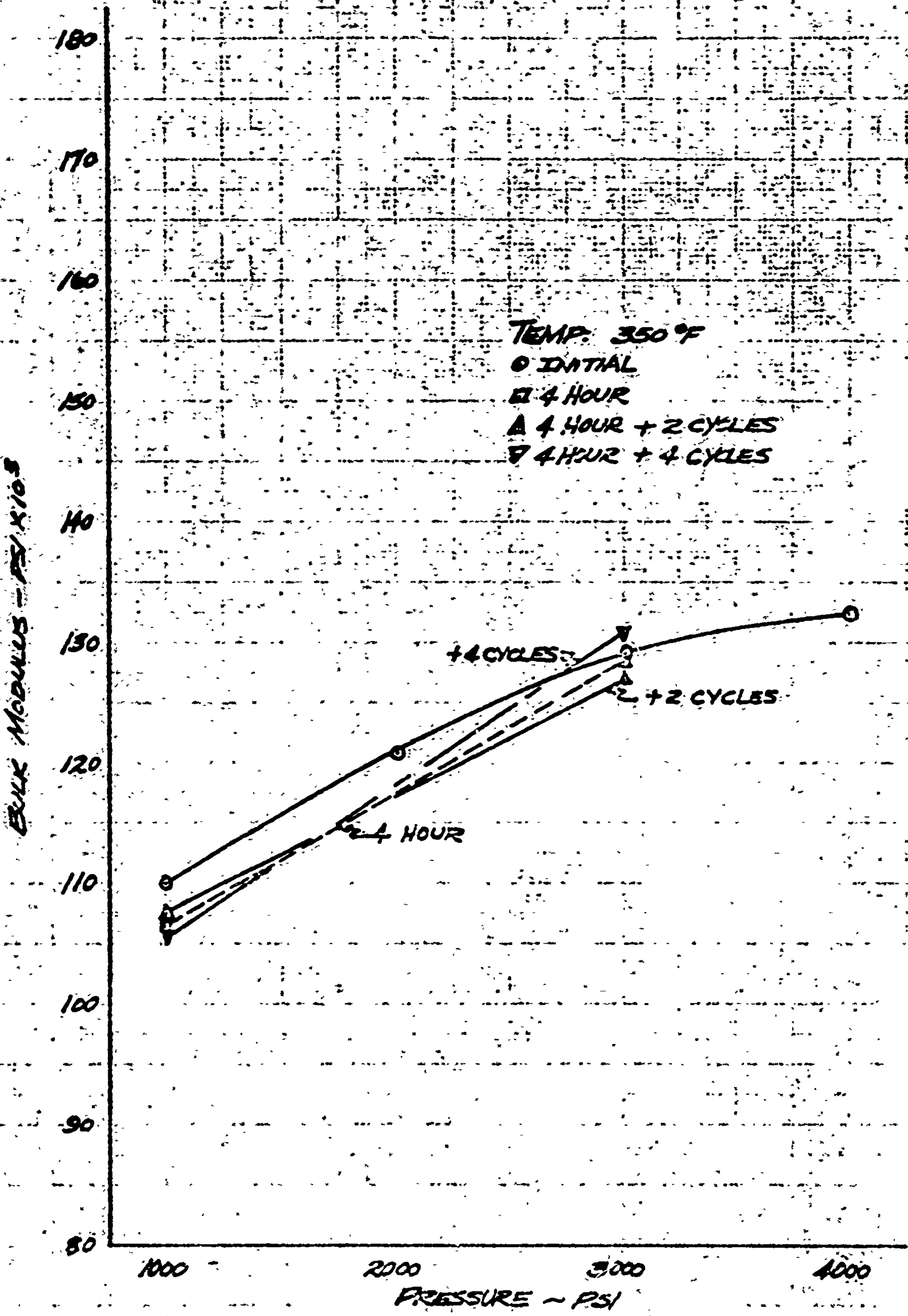


CALC			REVISED	DATE	BULK MODULUS VS TIME SYSTEM WSX-6885	FIG.39 D6-58362TN
CHECK						
APR						
APR					THE BOEING COMPANY	PAGE 54

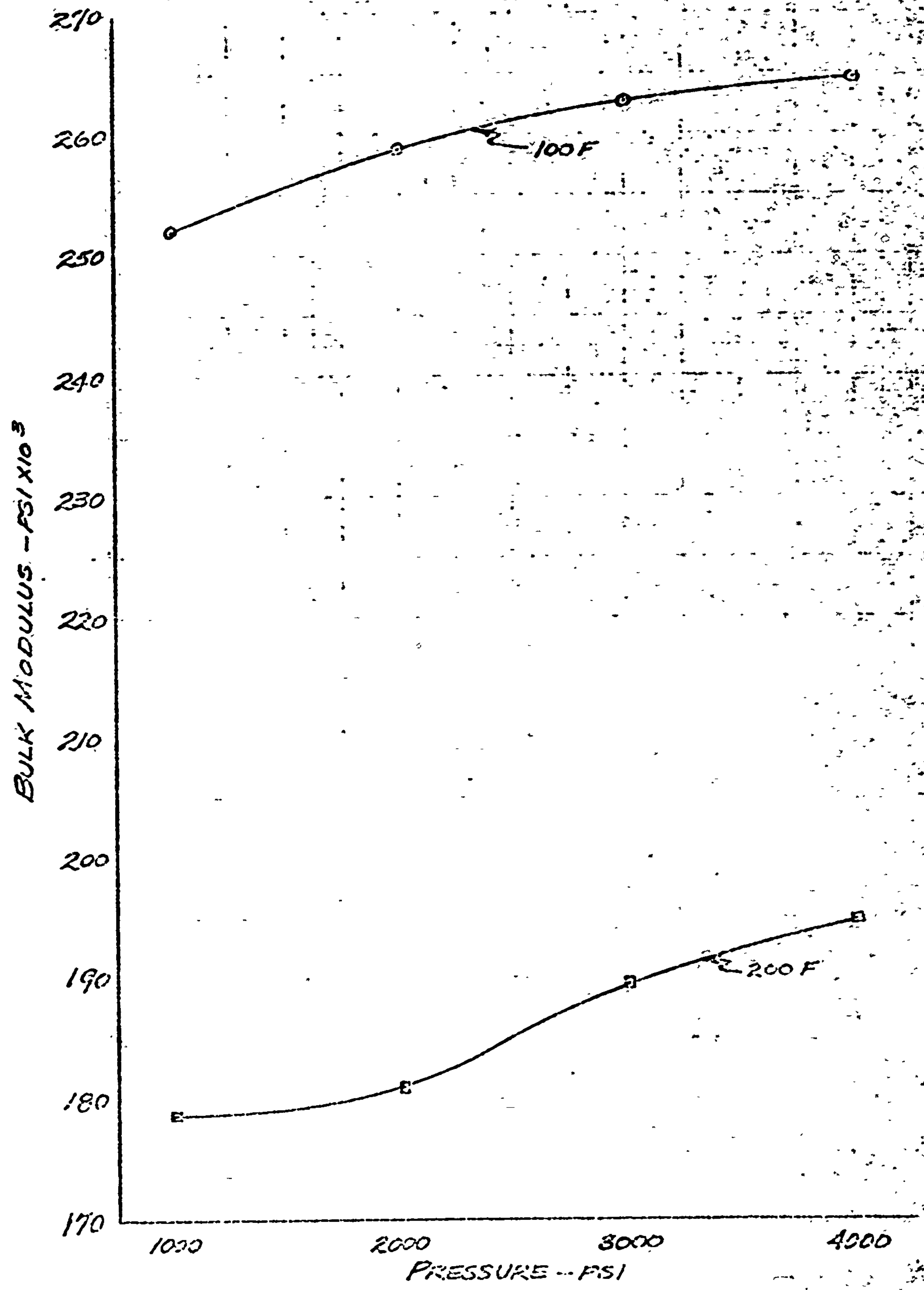
TD 461 C-R4



CALC			REVISED	DATE	SYSTEM DATA WITH FOUR HOUR CYCLING WSX-6885	FIG 40
CHECK						
APR						D6-58362TN
APR					THE BOEING COMPANY	PAGE 55

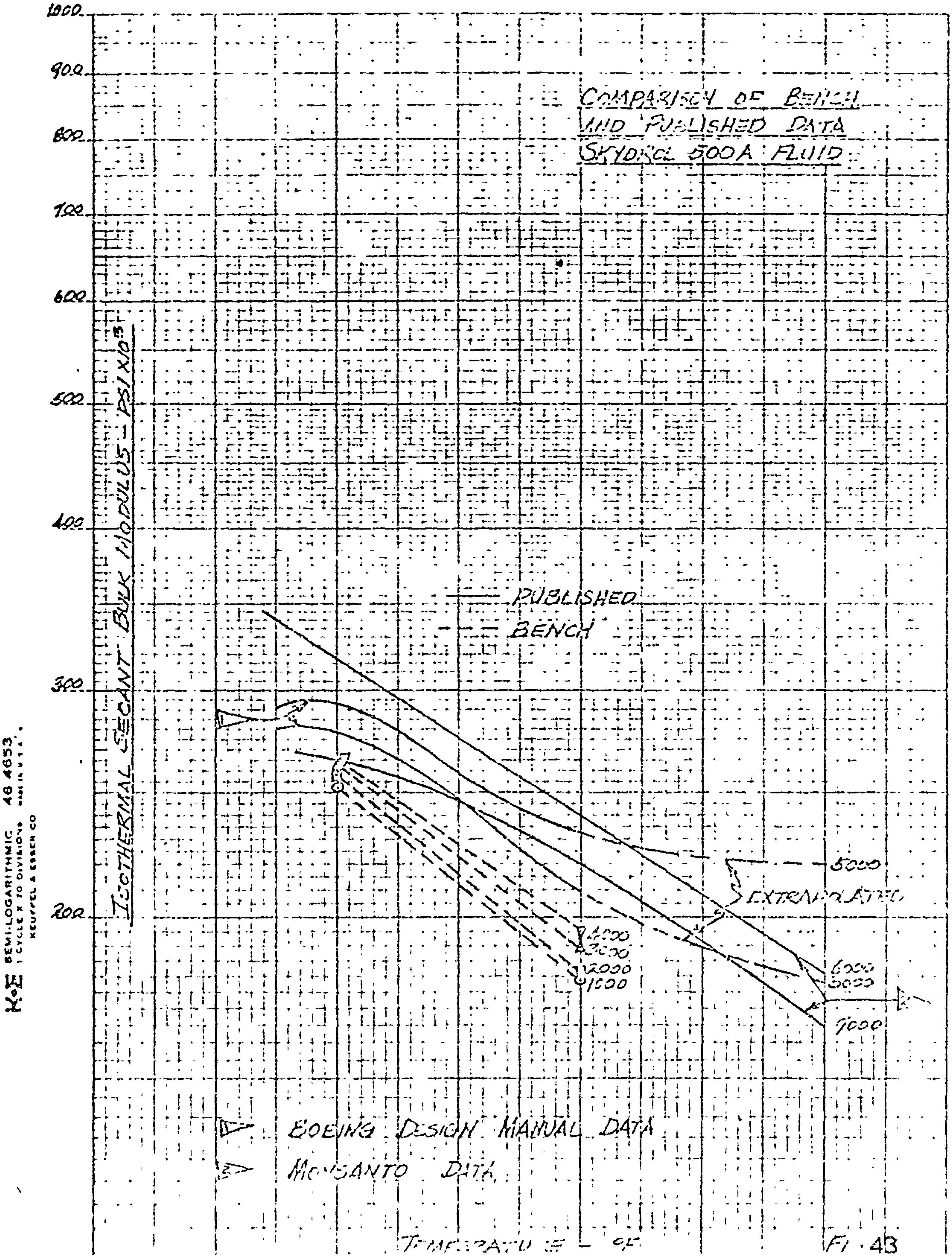


CALC			REVISED	DATE	SYSTEM DATA WITH FOUR HOUR CYCLING WSX-6885	FIG. 41
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 56
APR						



			REVISED	DATE		
CALC					BENCH DATA	FIG 42
CHECK					SKYDROL 500A	D6-58362TN
APR					THE BOEING COMPANY	PAGE 57
APR						

10 41 C-R1



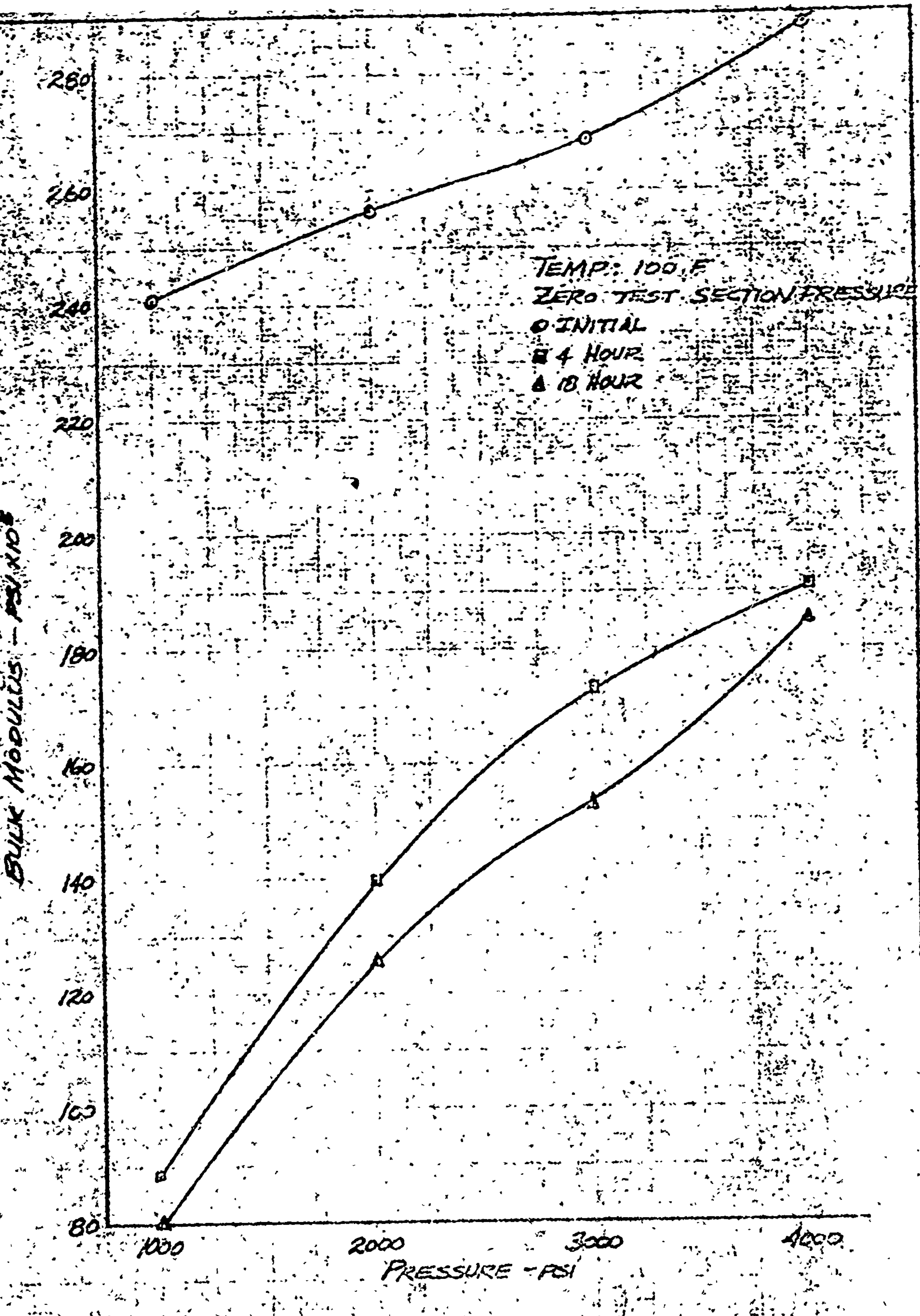
COMPARISON OF BENCH AND PUBLISHED DATA SKYDROL 500A FLUID
ISOTHERMAL SECANT BULK MODULUS – PSI X10^3
PUBLISHED
BENCH
5000
EXTRAPOLATED
4000
3000
2000
1000
6000
5000
7000
BOEING DESIGN MANUAL DATA
MONSANTO DATA
TEMPERATURE – °F
1000
900
800
700
600
500
400
300
200
100
0
100
200

Fig. 43

by the 4 hour and 18 hour values (Figures 44 and 45). With a 160 psi test section pressure during the dormant periods, the bulk modulus data was repeatable within the accuracy of test measurements (Figures 46 and 47). Comparing this data with the WSX-6885 data illustrates the similar trend mentioned previously. This comparison also illustrates that due to the similar results with pressurization the same effect could possibly be realized with fluids other than WSX-6885 and Skydrol 500A. Examination of the variation of bulk modulus with time for Skydrol 500A also shows the effect of pressurization with the 4 and 18 hour values varying little from the initial values (Figures 48 through 51).

For Skydrol 500A, cycling following the four hour dormant period yielded similar results at both 100 F and 200 F. The four hour data decreased markedly from the initial data. Nearly complete recovery occurred following two cycles, with complete recovery after two additional cycles (Figures 52 and 53). At both temperatures, the slope of the four hour curves increased sharply but decreased with cycling to closely approximate the initial curve slope.

In cycling with WSX-6885 and Skydrol 500A the fluid which was not initially in the test section and subjected to the pressurization during measurement and to test temperatures during the dormant periods enters the test section. After two cycles a portion of this fluid remains in the test section. Assuming no mixing, approximately 5 cubic inches of fresh fluid remains in the test section (volume $\approx$ 24 cubic inches) (Figure 54). As can be seen, this volume of oil is exchanged with each pair of full stroke cycles. This fluid could possibly alter the bulk modulus values obtained



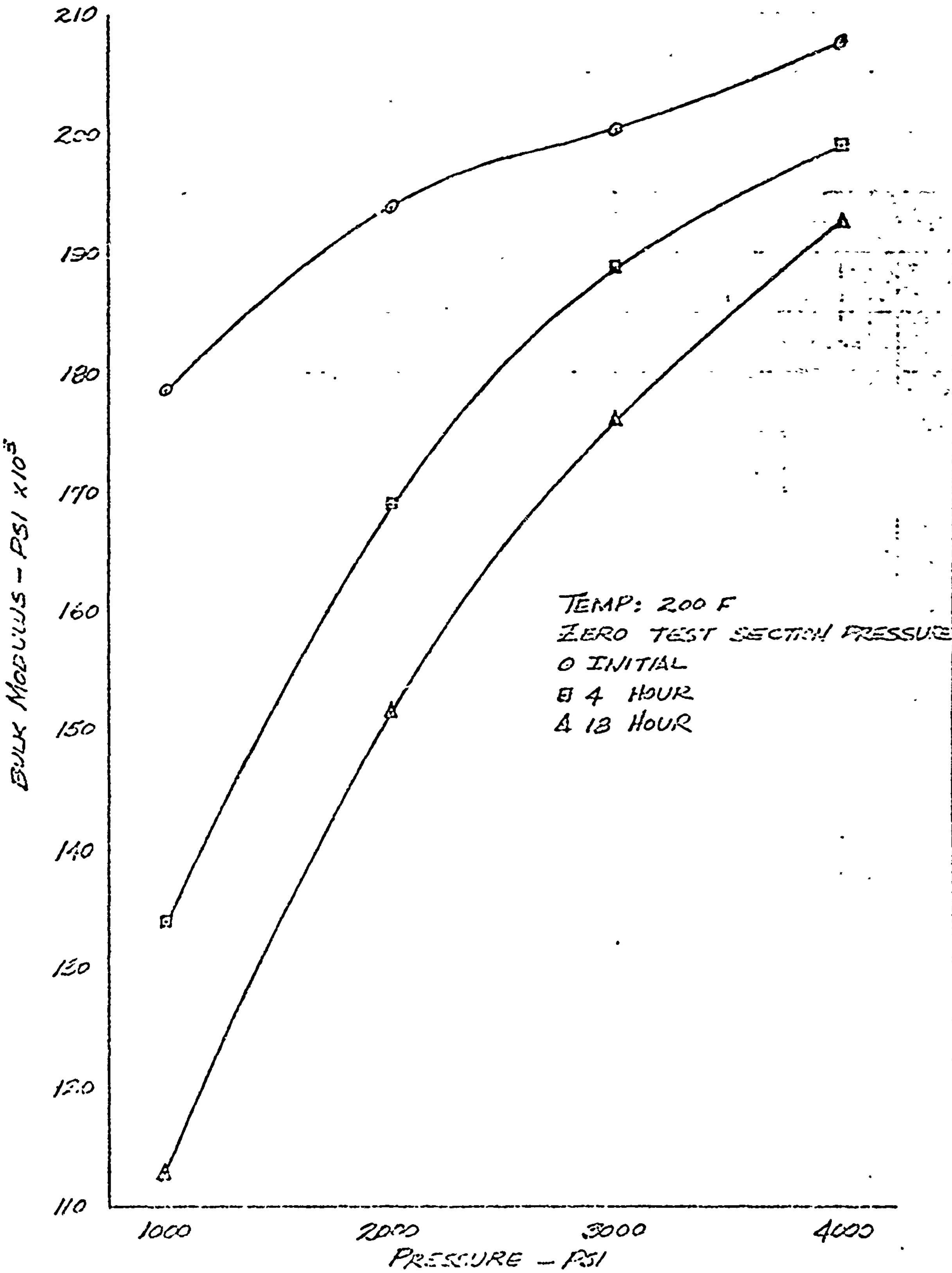
CALC			REVISED	DATE
CHECK				
APR				
APR				

BULK MODULUS DATA
SYSTEM SKYDROL 500A

FIG 44
D6-58362TN

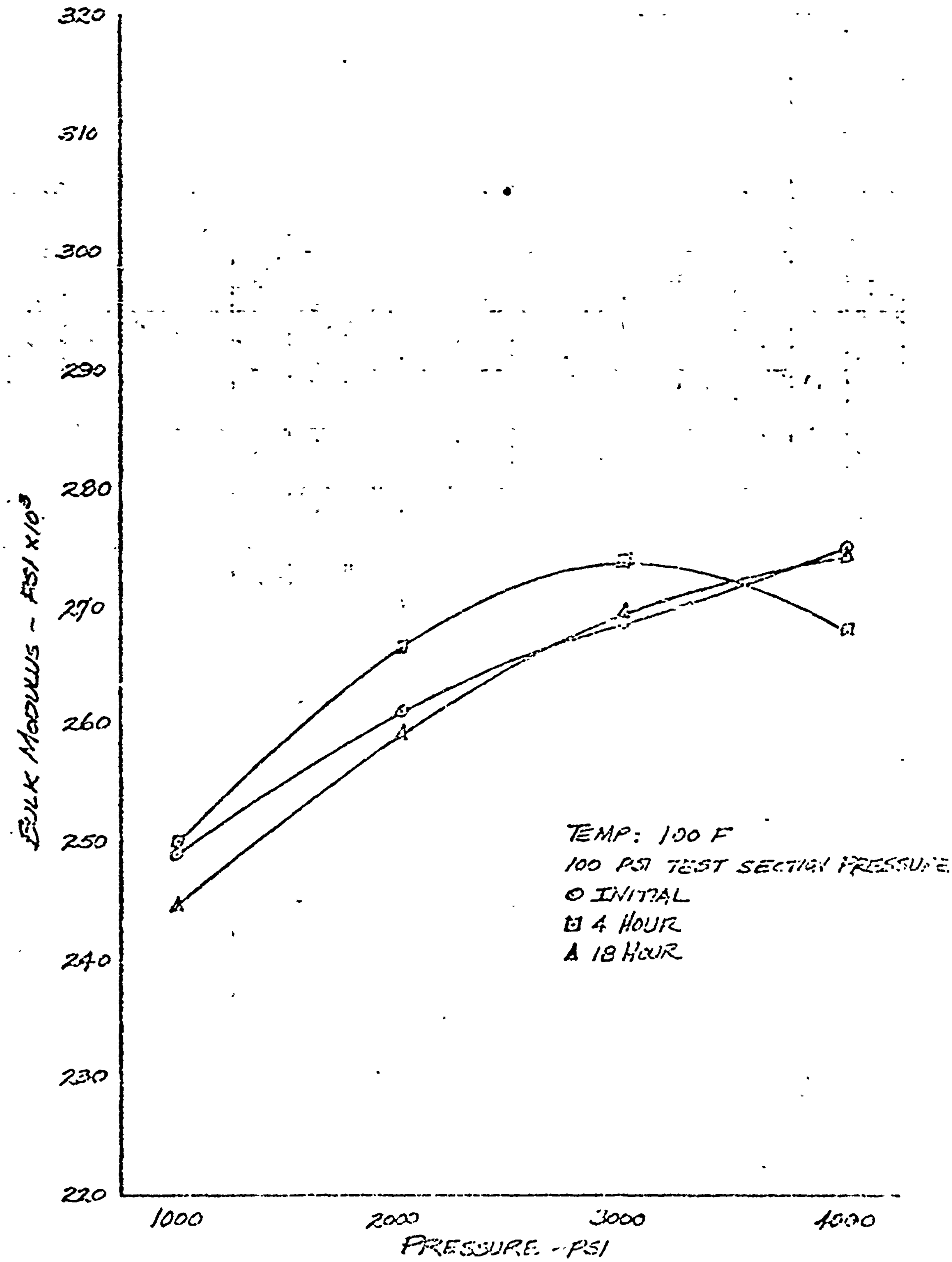
THE BOEING COMPANY

TD 441 C-14

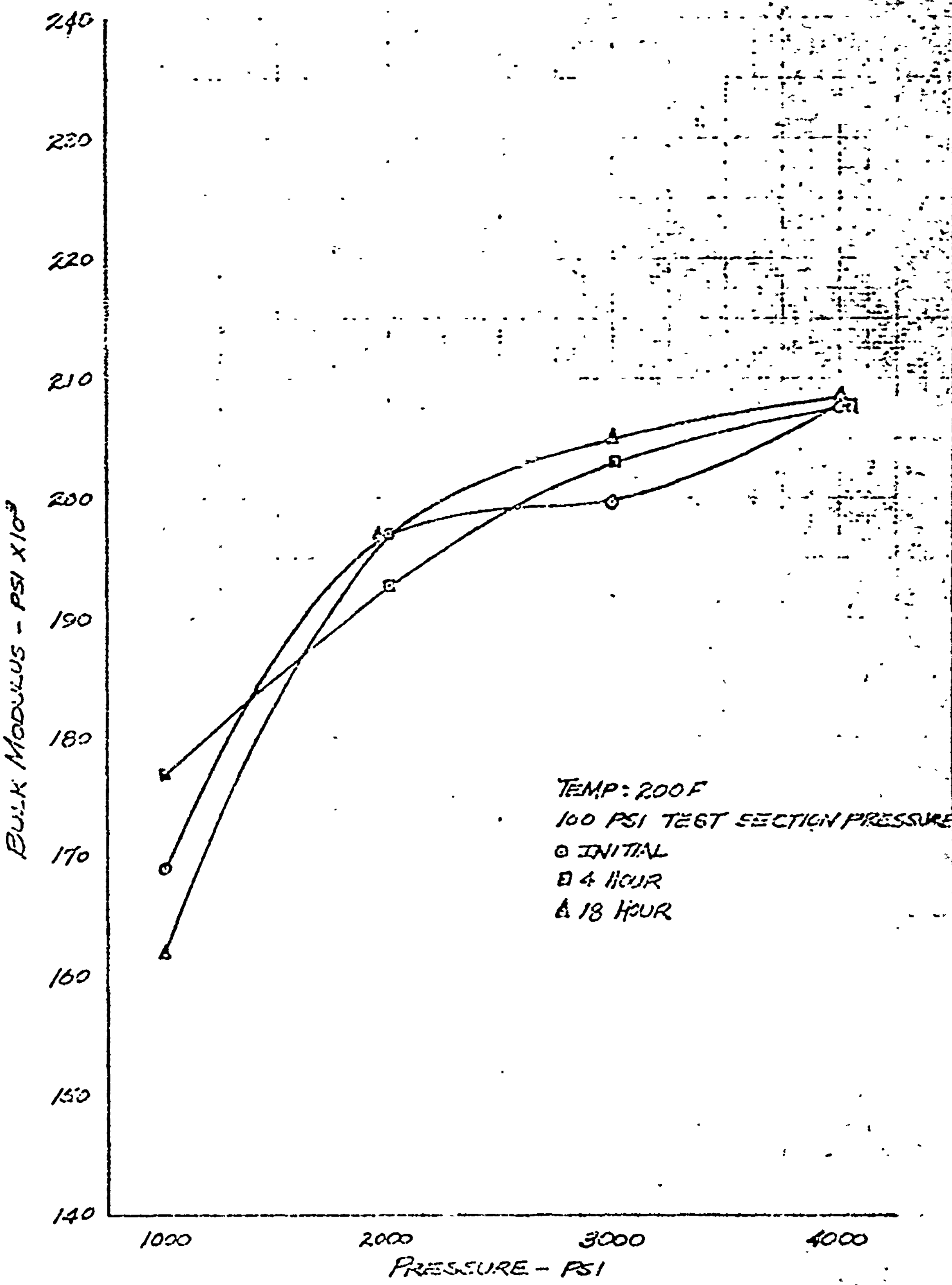


CALC			REVISED	DATE	BULK MODULUS DATA	FIG 45
CHECK					SYSTEM SKYDROL 500A	
APR						D6-58362TN
APR					THE BOEING COMPANY	PAGE 61

TD 461 C R4

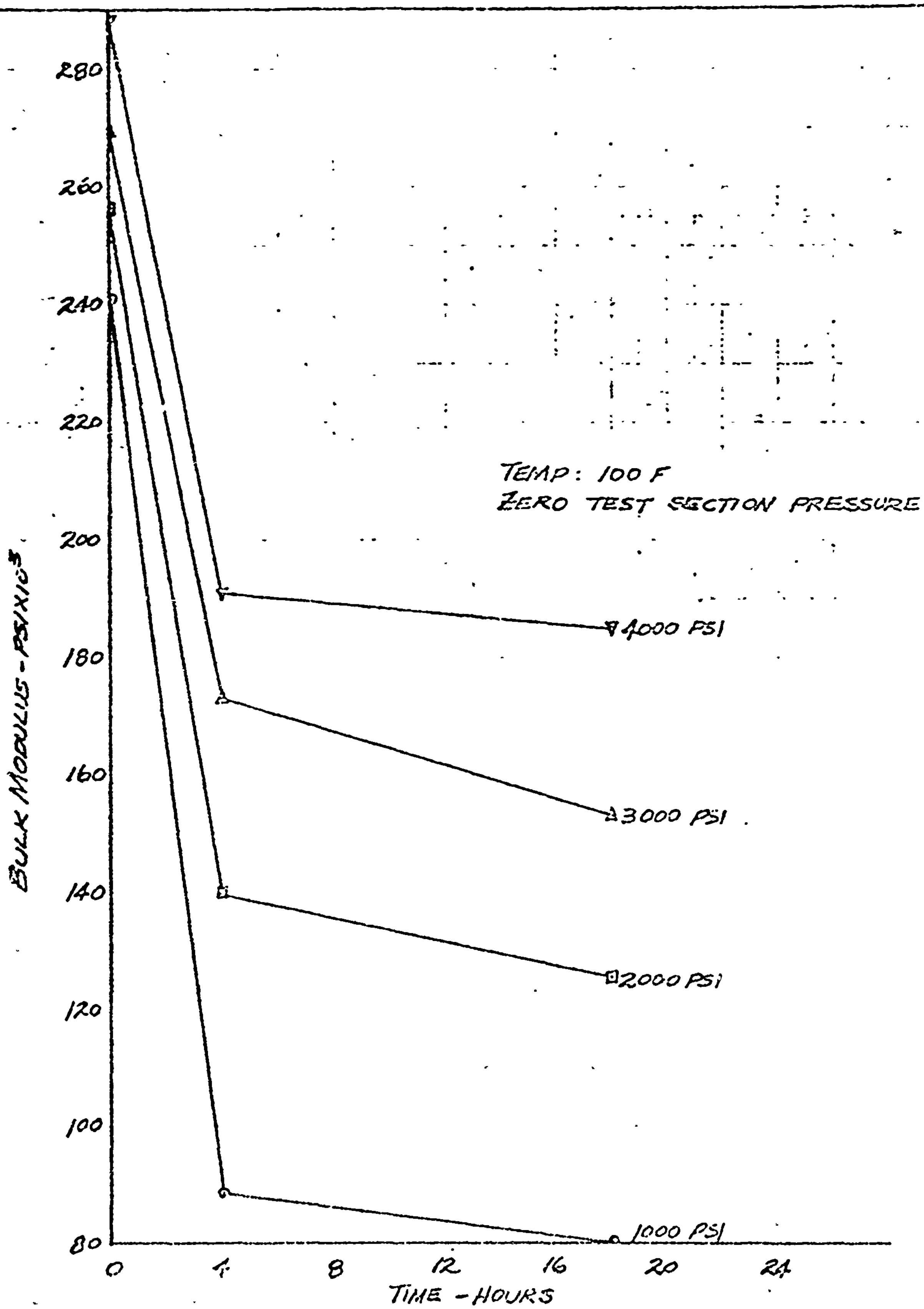


CALC			REVISED	DATE	BULK MODULUS DATA SYSTEM SKYDROL 500A	FIG 46
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 62
APR						



CALC			REVISED	DATE	BULK MODULUS DATA	FIG 47
CHECK					SYSTEM - SKYDROL 500A	D6-58362TN
APR						
APR					THE BOEING COMPANY	PAGE 63

TD 461 C-R4



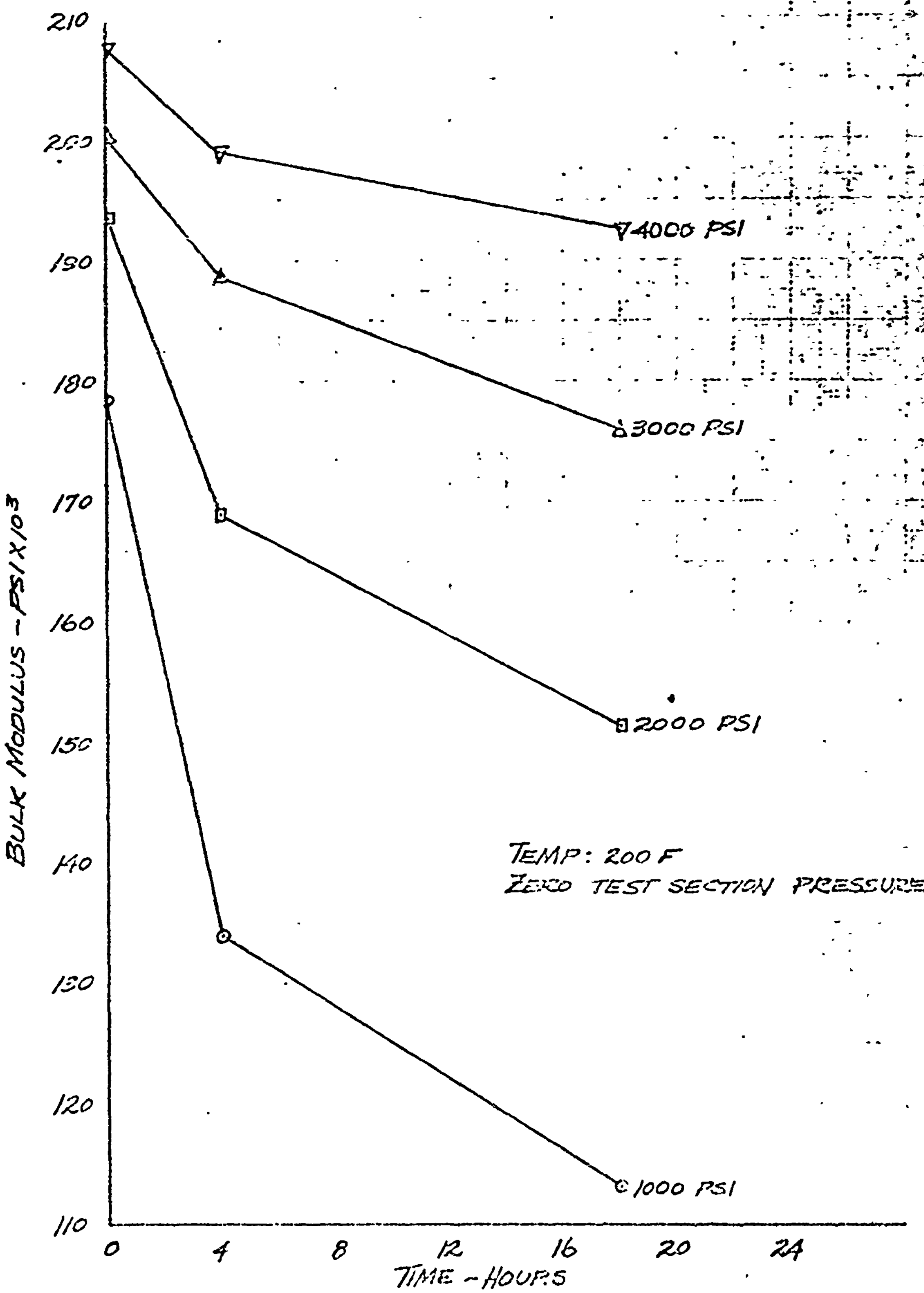
CALC			REVISED	DATE
CHECK				
APR				
APR				

BULK MODULUS VS TIME
SYSTEM SKYDROL 500A

THE BOEING COMPANY

FIG 48

TD 461 C-R4



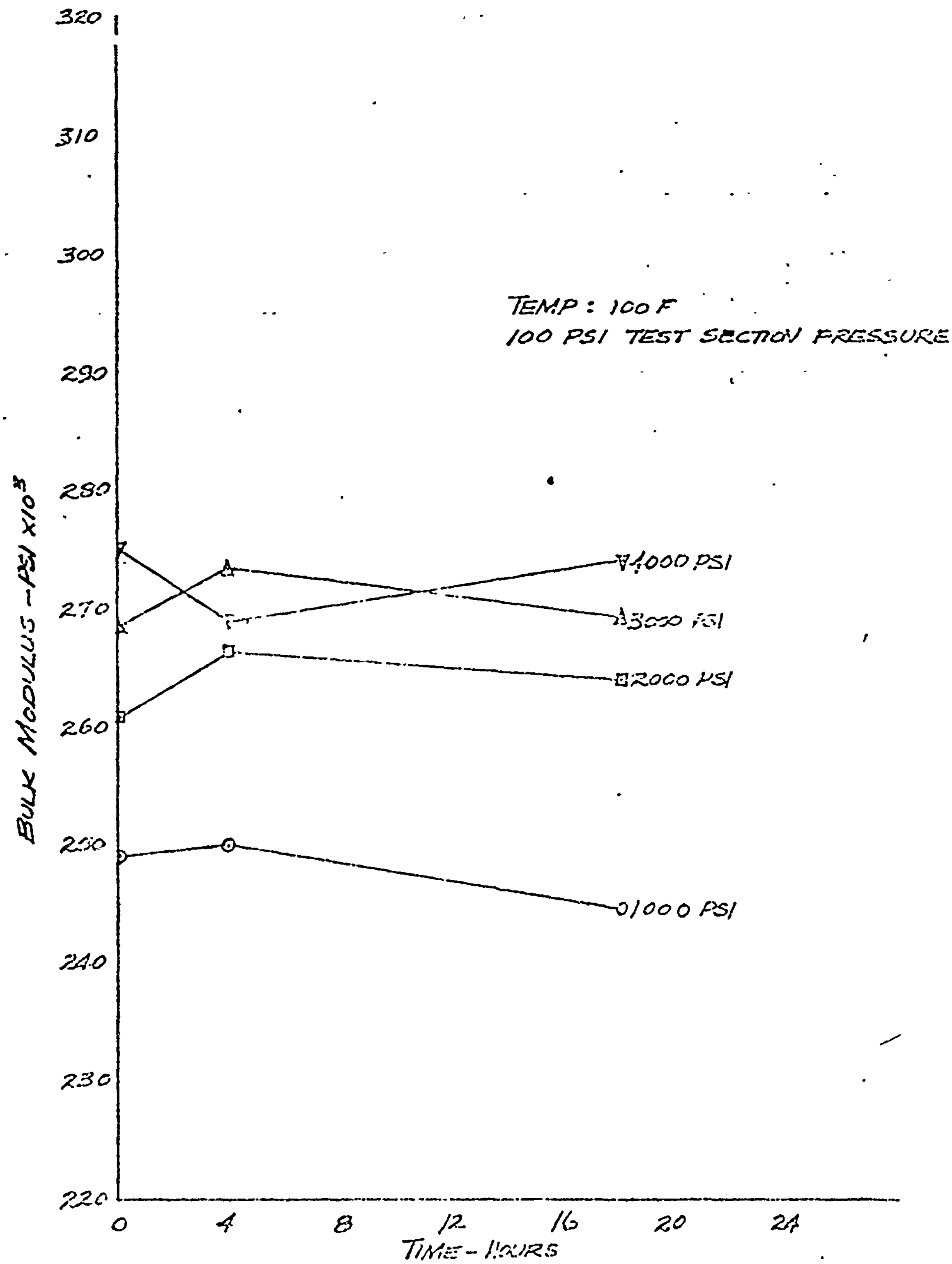
BULK MODULUS VS. TIME
SYSTEM SKYDROL 500A

FIG 49

D6-58362TN

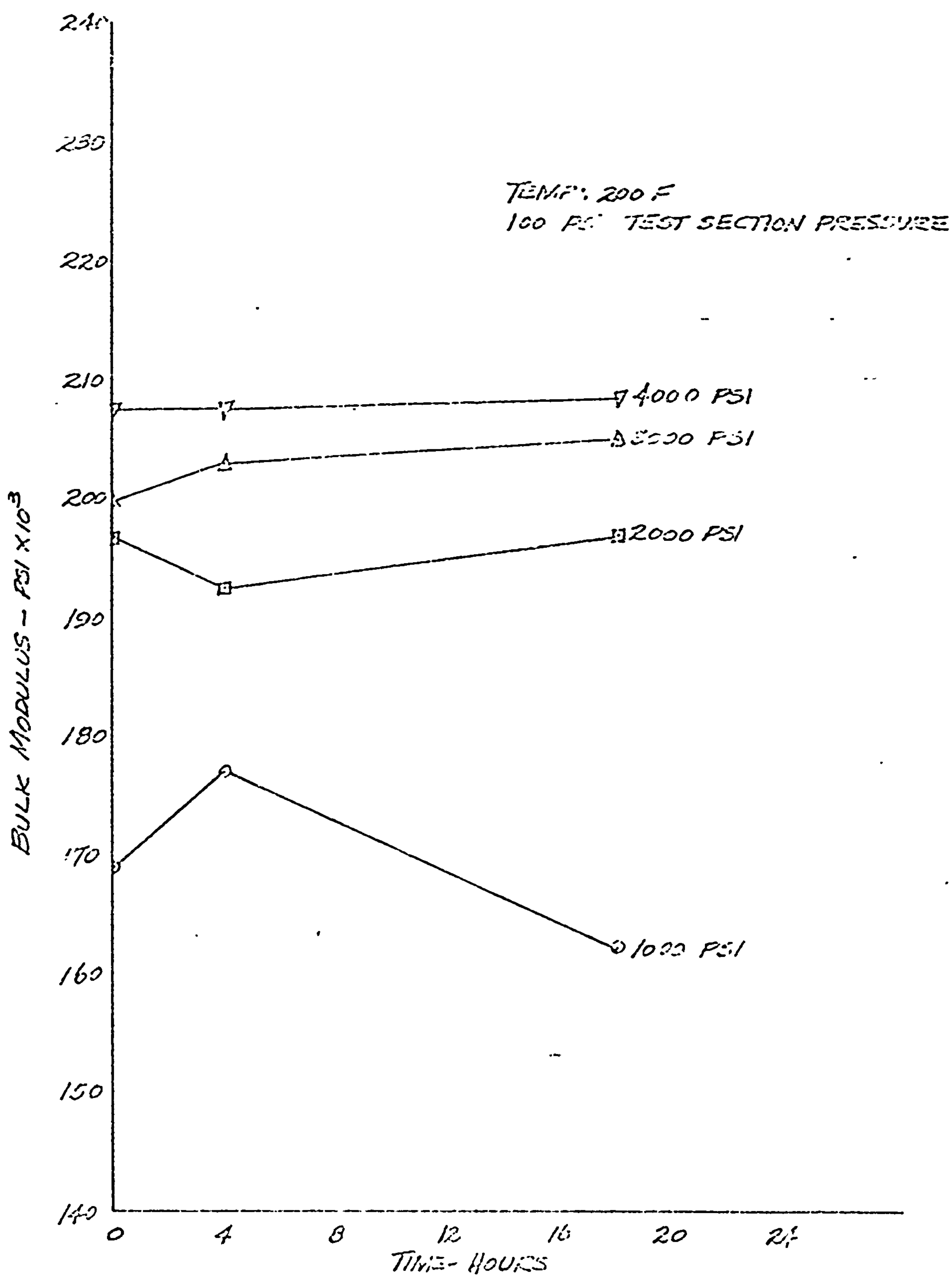
THE BOEING COMPANY

TD 461 C-R4



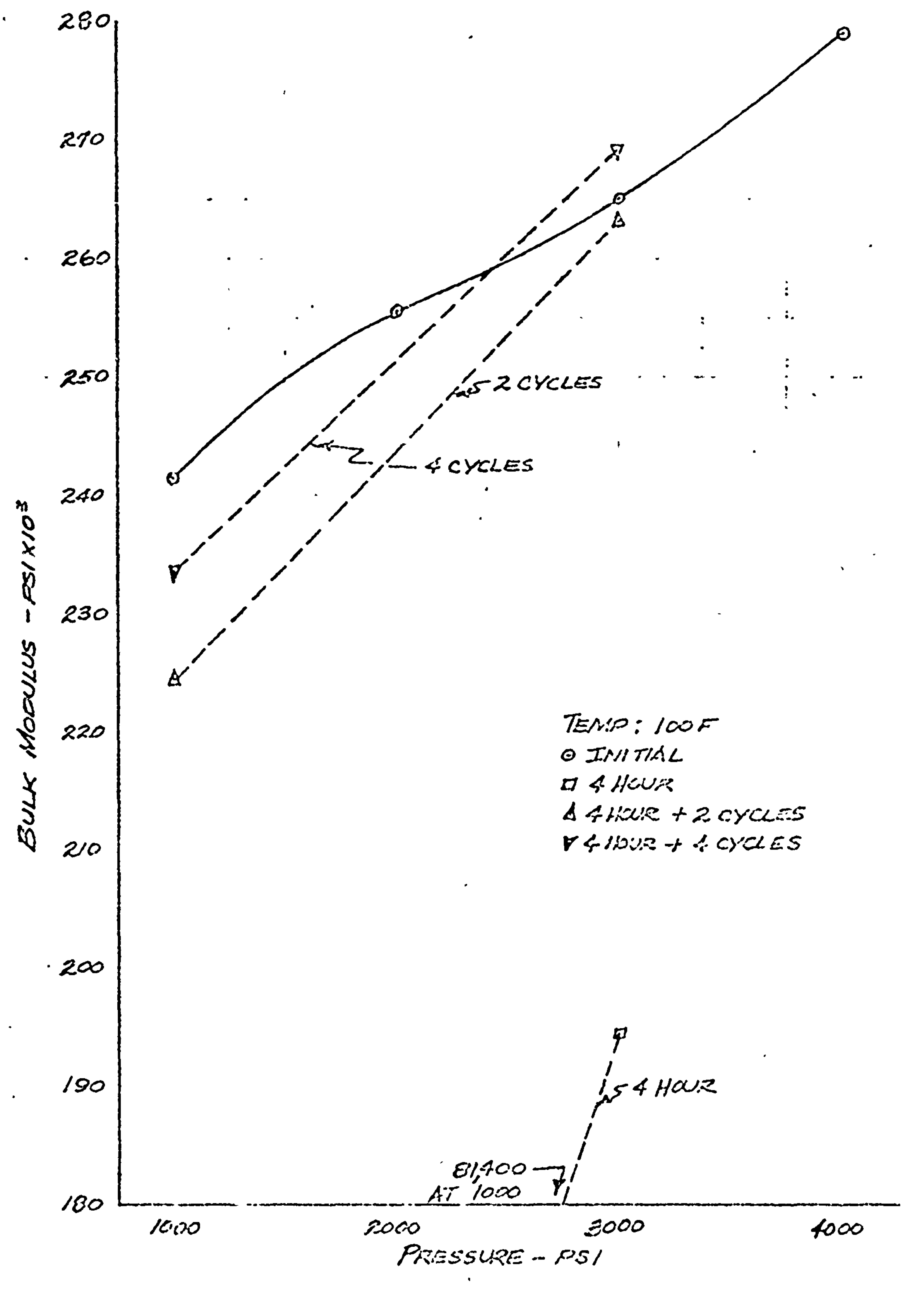
CALC			REVISED	DATE	BULK MODULUS VS TIME SYSTEM SKYDROL 500A	FIG 50
CHECK						D6-58362TN
APR					THE BOEING COMPANY	PAGE 66
APR						

TD 4el CAN



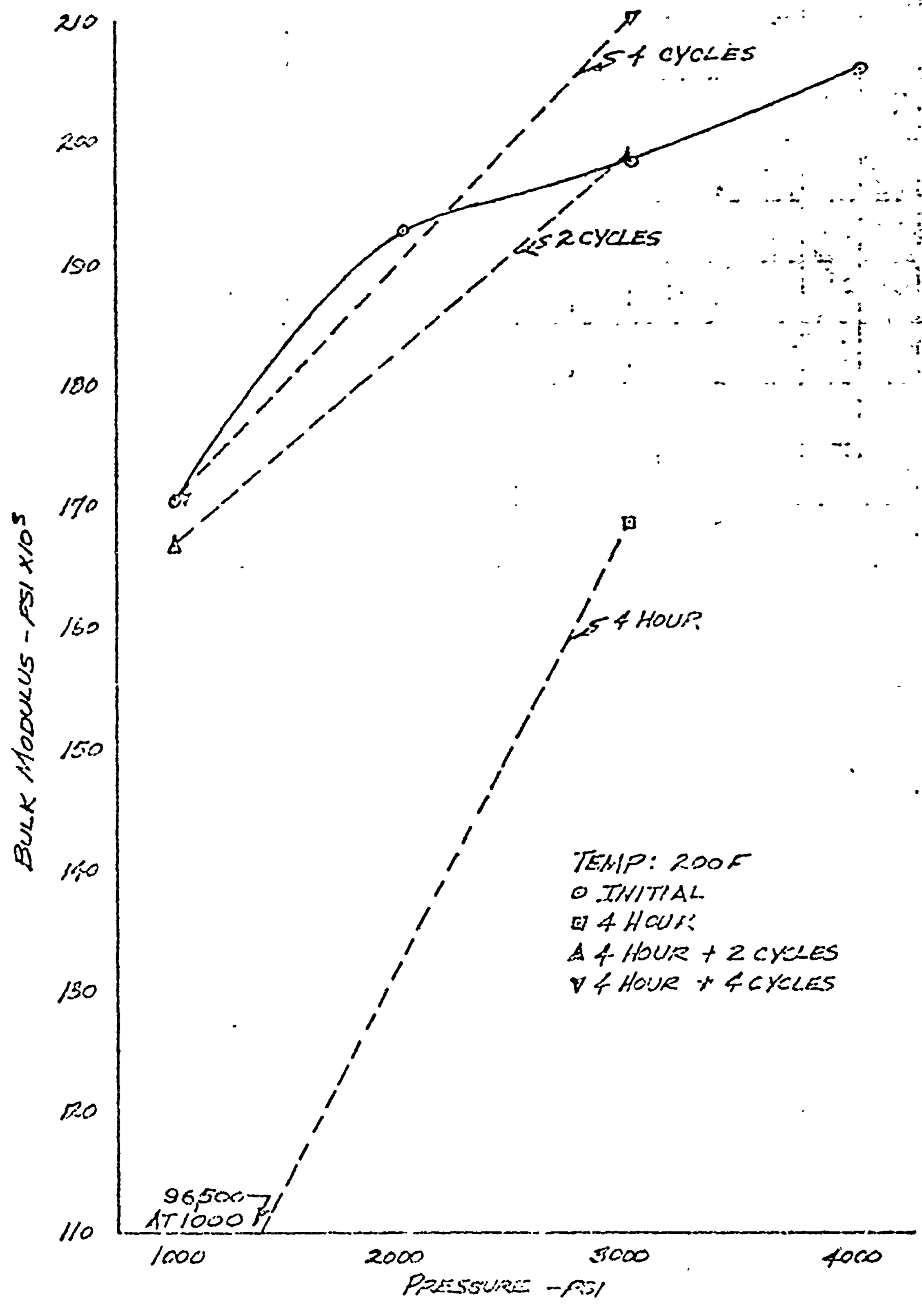
					BULK MODULUS VS TIME SYSTEM SKYDROL 500A	FIG 51
						D6-58362TN
					THE BOEING COMPANY	67

TD 461 C-R4



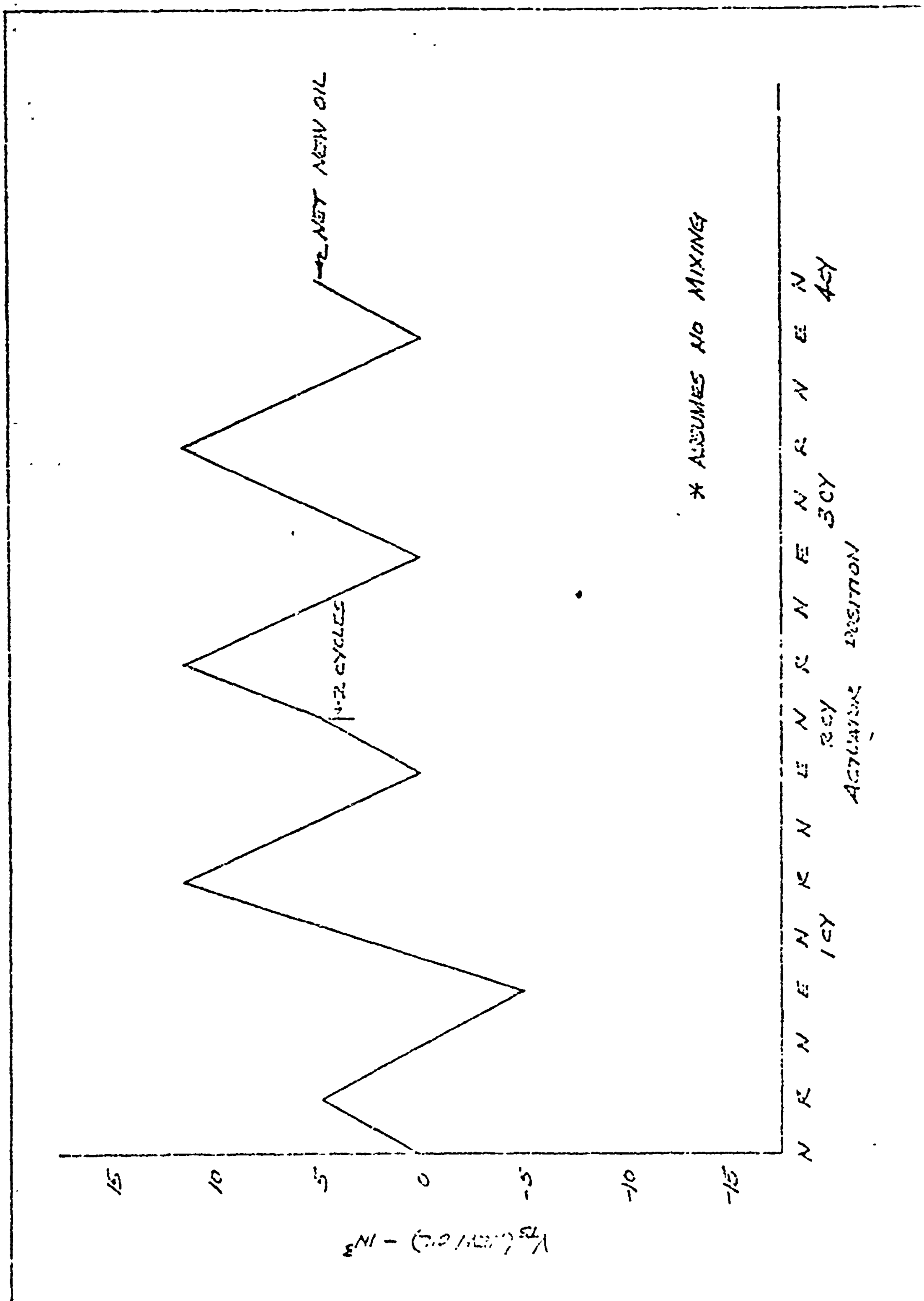
CALC			RELATED	DATE	SYSTEM DATA WITH FOUR HOUR CYCLING SKYDROL 500A	FIG 52
CHECK						D6-58362TN
APR						
APR					THE BOEING COMPANY	PAGE 68

TD 41 C-R1



CALC			REVISED	DATE	SYSTEM DATA WITH FOUR HOUR CYCLING SKYDROL 500A	FIG 53
CHECK						D6-58362TN
APD					THE BOEING COMPANY	PAGE 69
APD						

TD 4.1 C84



TEST SECTION OIL CHANGE VS. ACTUATOR CYCLING

FIG. 54

D6-58362TN

THE BOEING COMPANY

due to its different temperature and possibly different content of dissolved and entrained air.

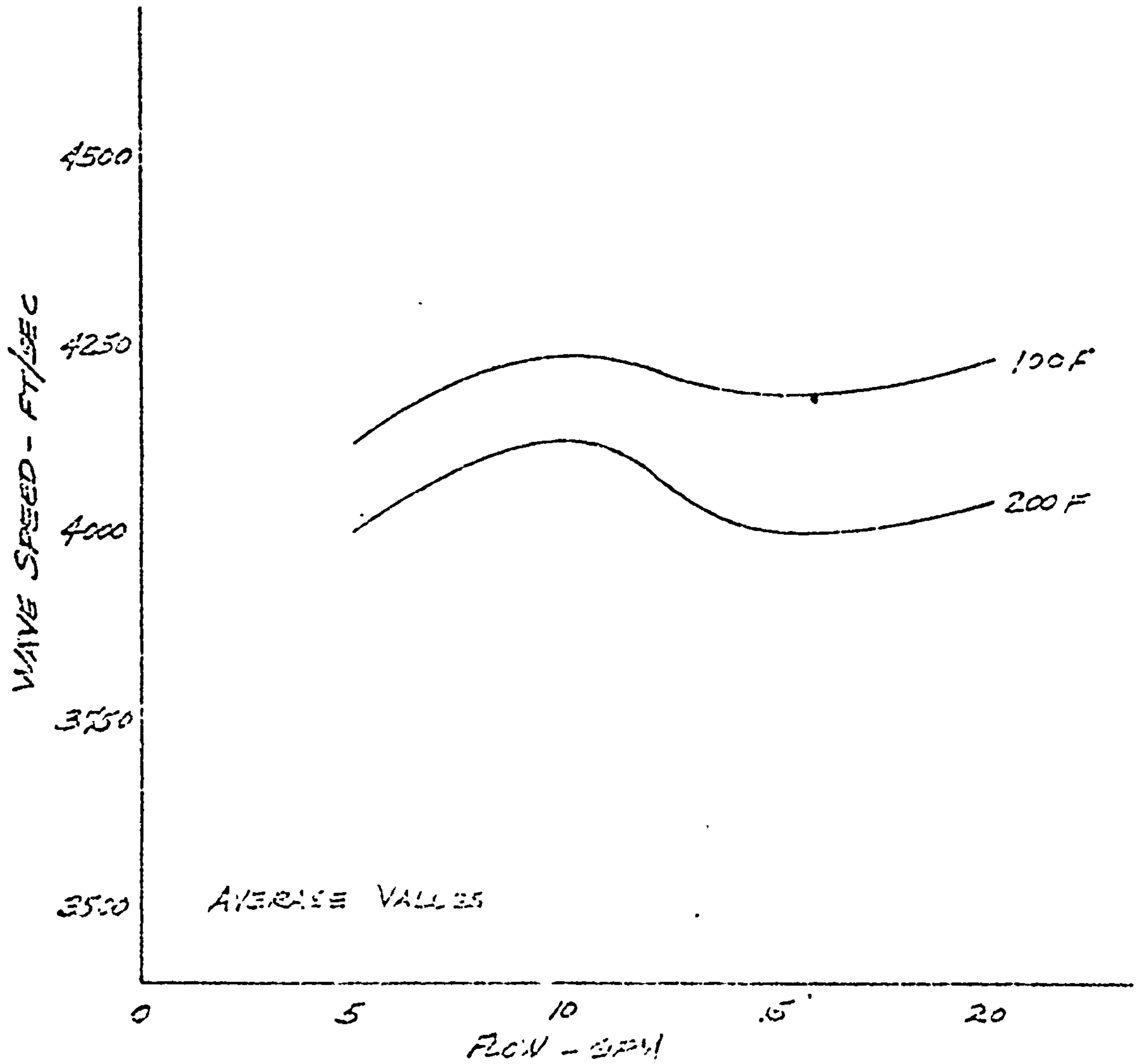
2. **Wave Speed Measurements with a Flowing Fluid**

In analyzing the test data, bulk modulus values were computed based on the wave speeds obtained from oscillograph recordings. The wave speed is affected by temperature but is not a function of flow rate (Figures 55 and 56). An average bulk modulus was computed for identical flow rate and temperature conditions. These values are compared with published data and tabulated (Figures 57 and 58). Adiabatic tangent bulk modulus data for WSX-6885 fluid was obtained from information available within Boeing (Figures 59 and 60). Comparable data for Skydrol 500A was obtained from Monsanto publications (Figures 60 and 61).

The maximum deviations of test data to published data was 15.6 percent at 100 F for WSX-6885 and 13.8 percent at 100 F for Skydrol 500A (Figures 57 and 58). The following discussion may in part explain these deviations.

In determining the bulk modulus by this method, the most accurate value would be obtained from a single instantaneous disturbance. This would be the ideal case and would theoretically be a vertical pressure trace on the oscillograph recording at time zero. A disturbance of this type is not possible due to hardware limitations. However, this condition can be approached by utilizing the most rapidly closing valve obtainable. A rapidly closing valve is one which has a closure time of less than $2L/a$, (*)

(*)(SEE APPENDIX A)

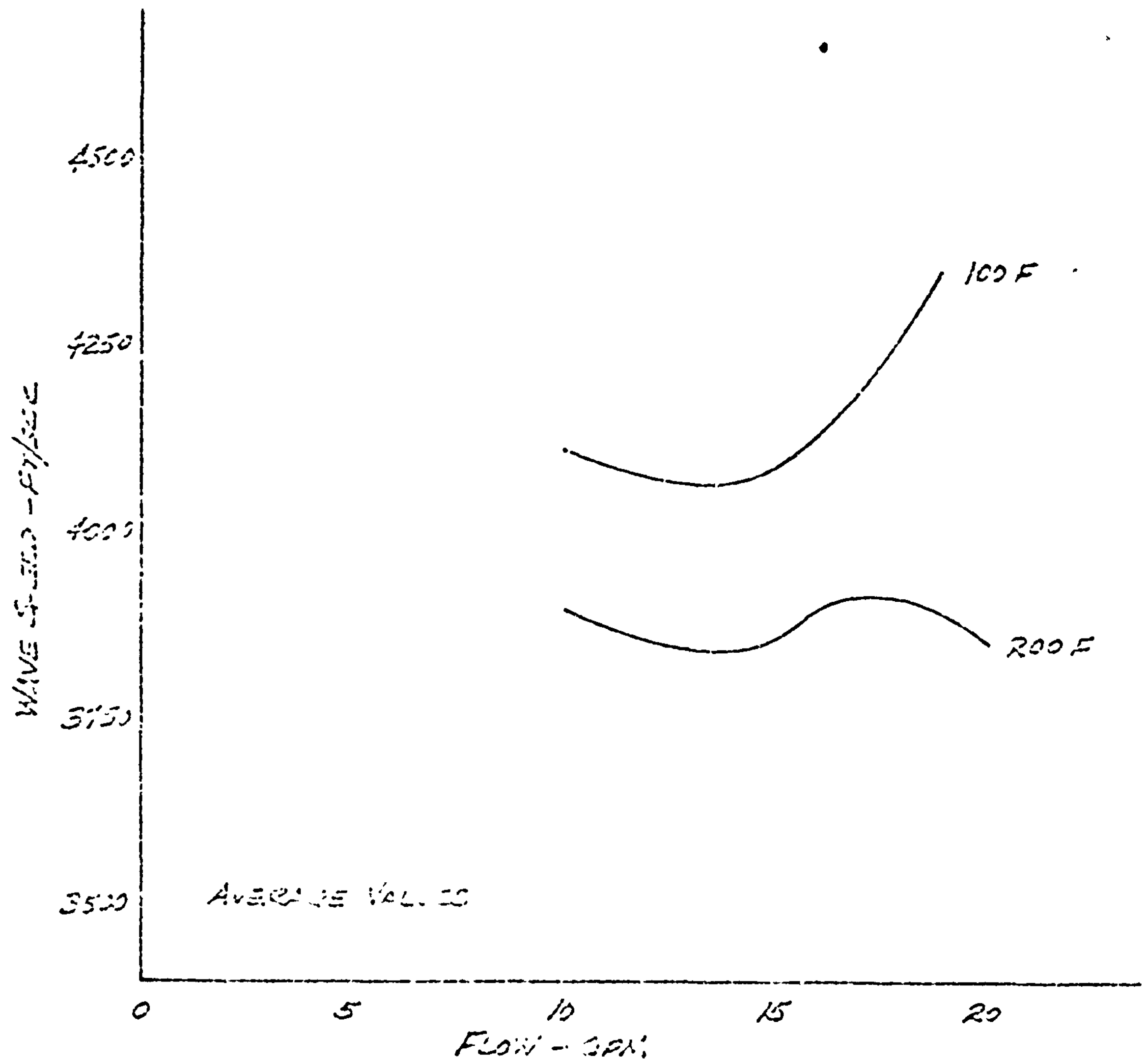


WAVE SPEED VS. FLOW
WSX-6585 FLUID

Fig 55

D6-58362TN

THE BOEING COMPANY



56
D6-58362TN

BULK MODULUS DATA - FLOWING FLUID

WSX-6885 FLUID

RUN	Q gpm	P PSI	T °F	a FT/SEC	LABORATORY DATA B_S PSI	PUBLISHED DATA B_S PSI ▷1	% DEVIATION
1	20	2500	123	4230	246,000	260,000	5.4
2	15	2800	113	4186	240,000	271,000	11.4
3	10	2888	122	4238	247,000	267,000	7.5
4	5	2888	111	4130	233,000	276,000	15.6
1	20	2813	197	4050	224,000	215,000	4.2
2	15	2812	195	4000	218,000	215,000	1.4
3	10	2900	195	4120	225,000	215,000	4.7
4	5	3150	193	4000	218,000	221,000	1.3

▷1 BOEING DATA REF. 5

FIG. 57

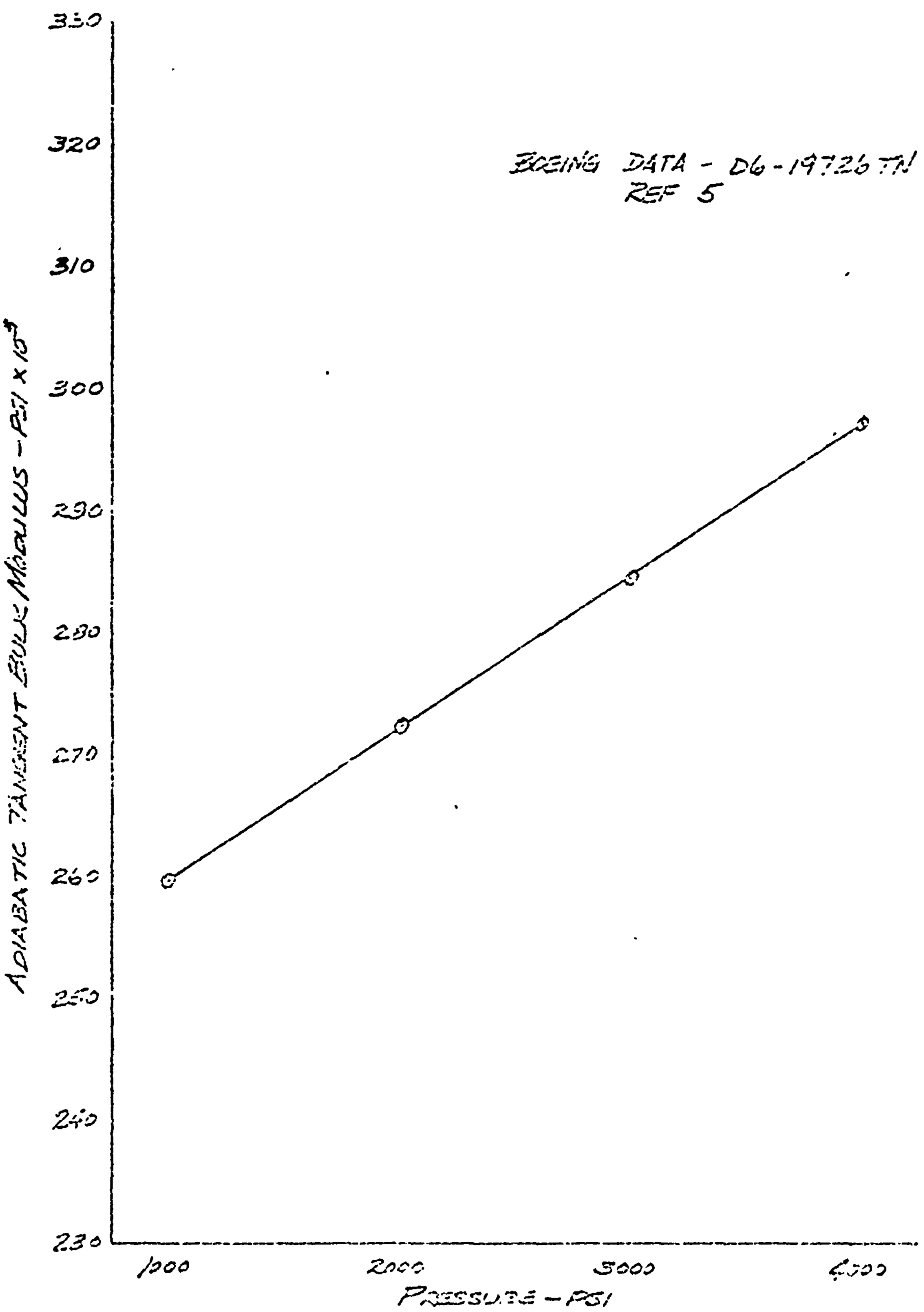
BULK MODULUS DATA - FLOWING FLUID

SKYDROL500A FLUID

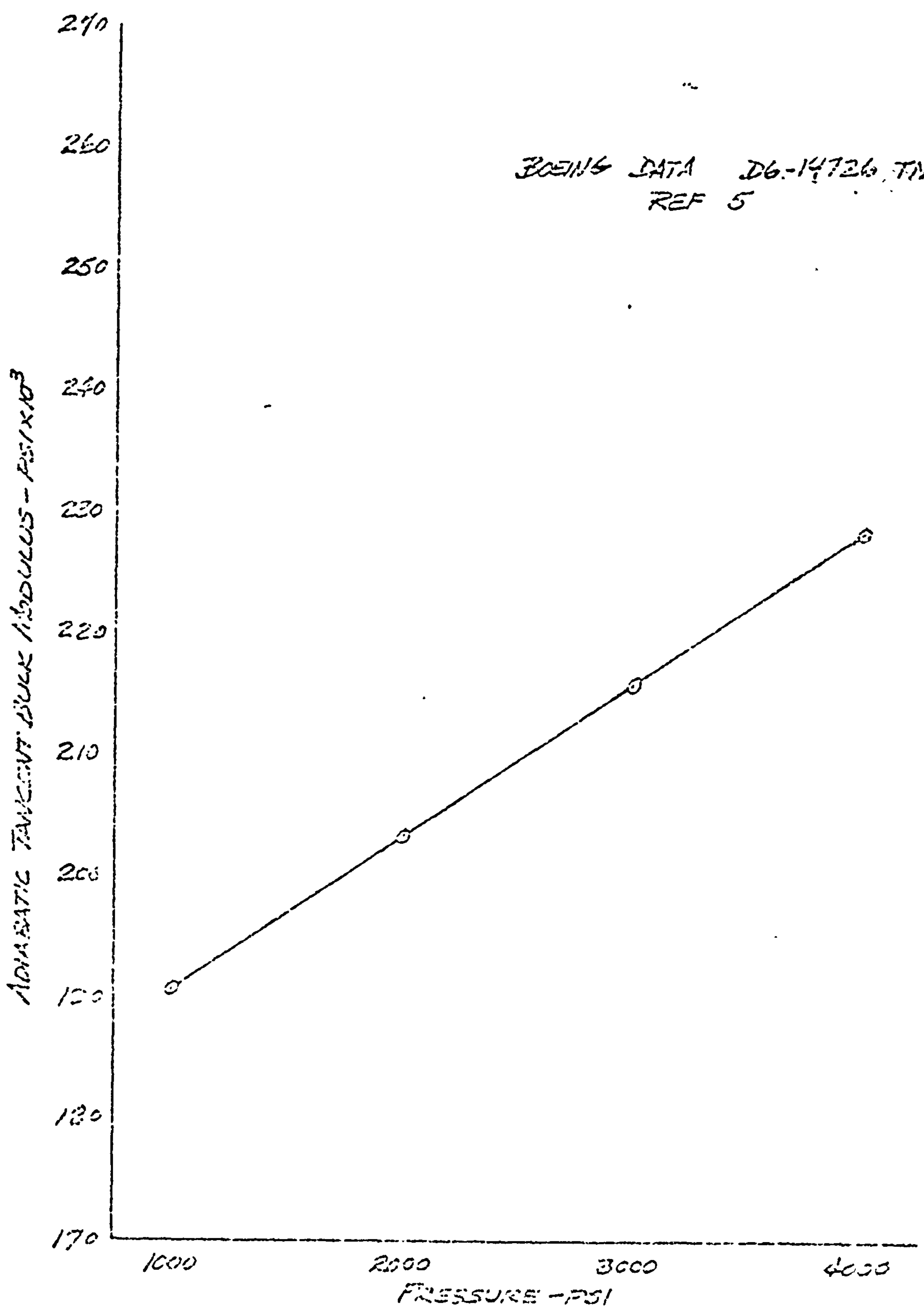
RUN	Q gpm	P PSI	T °F	a FT/SEC	LABORATORY DATA B_s PSI	PUBLISHED DATA B_s PSI [1]	% DEVIATION
1	20.0	2888	200	3850	215,000	214,000	0.4
2	17.2	2863	198	3975	229,000	214,000	7.0
3	15.0	2875	203	3835	214,000	214,000	0.0
4	10.0	3075	200	3900	220,000	216,000	1.9
1	18.75	2813	110	4360	297,000	296,000	0.3
2	15.0	2863	105	4085	256,000	297,000	13.8
3	10.0	2950	98	4105	259,000	298,000	13.5

[1] MONSANTO DATA

FIG. 58



WSX-3855 FLUID



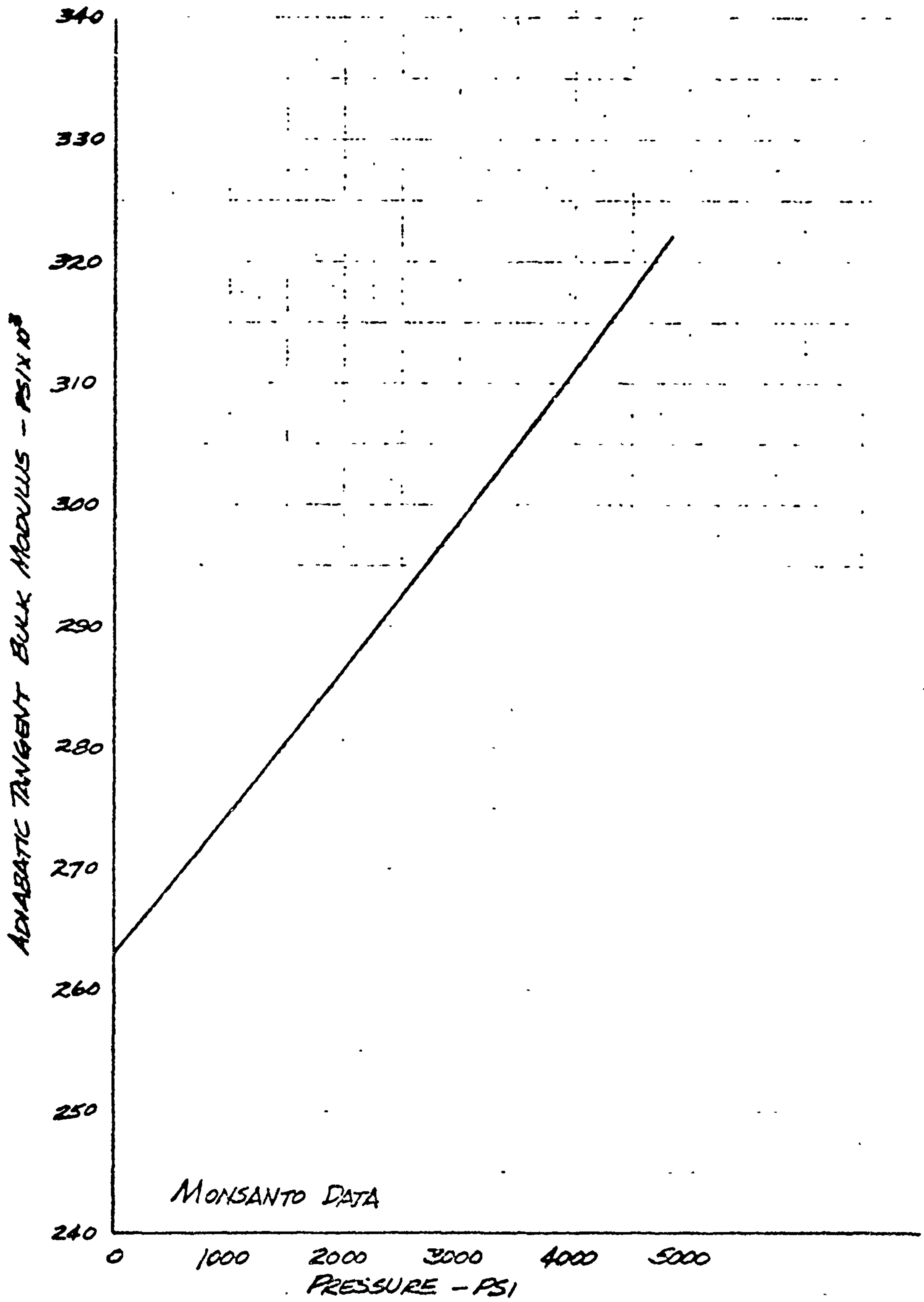
FLUID DATA - 200F

6335 FLUID

FIG. 60.

D6-58362TN

THE BOEING COMPANY



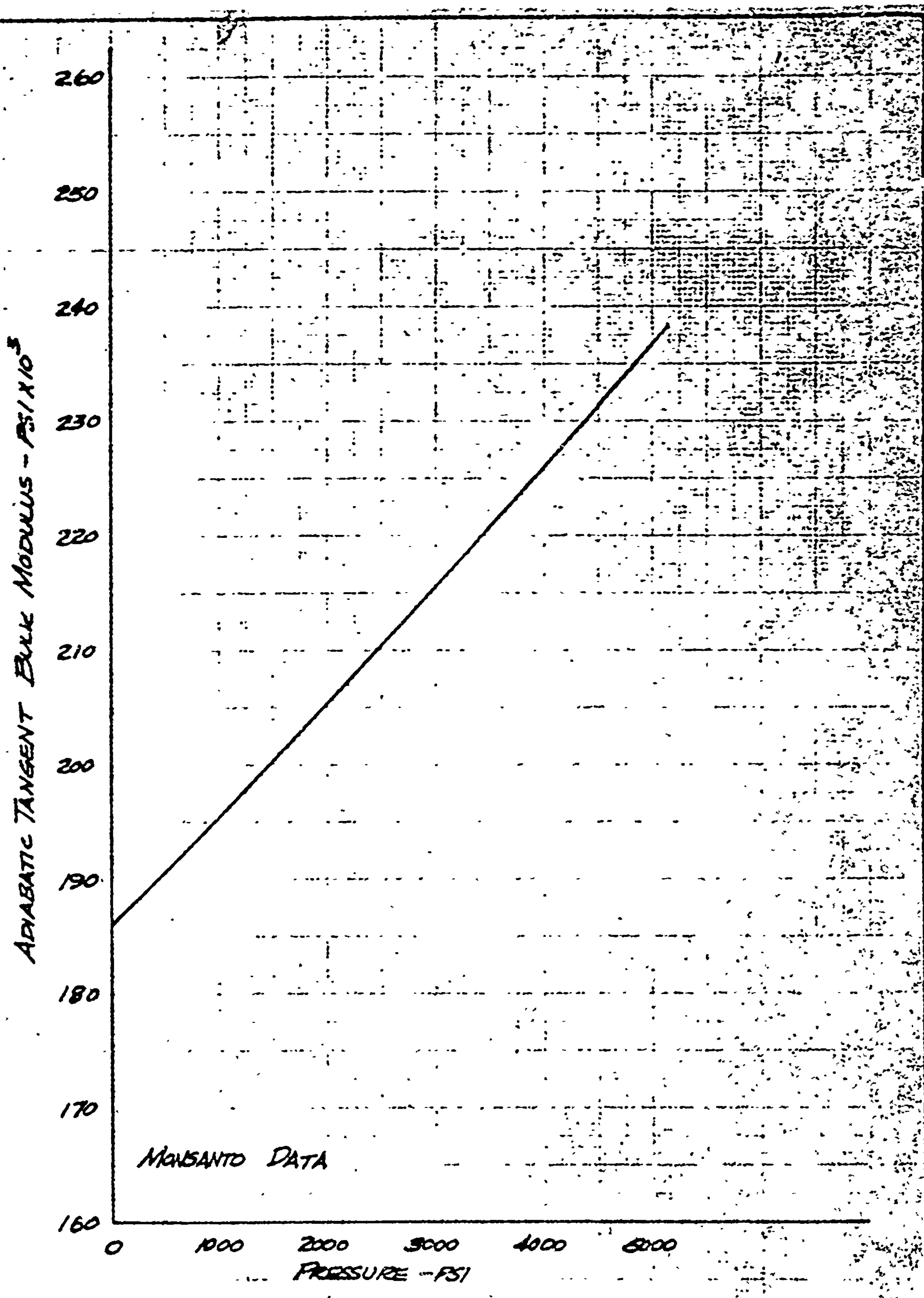
CALC			REVISED	DATE
CHECK				
APR				
APR				

PUBLISHED DATA – 100°F
SKYDROL 500A FLUID

THE BOEING COMPANY

FIG. 61

TD 461 C-R4



CALC			REVISED	DATE	PUBLISHED DATA - 200°F SKYDROL 500A FLUID	Fig. 62 D6-58362TN
CHECK						
APR					THE BOEING COMPANY	PAGE 79
APR						

this being the time required for the disturbance to transverse the length of the line and return. Construction of the valves utilized for these measurements prohibited determining the closure time. However, an estimate of this time may be obtained by observing the pressure traces. This was complicated by the fact that pump ripple was superimposed on these traces.

In testing with WSX-6335, the percentage of air in the fluid was obtained by use of the Seaton-Wilson "Airometer." Fluid samples of new and cycled fluid were taken, the cycled fluid being drawn from the system following 20 minutes of cycling and after the 4 and 18 hour dormant periods at a temperature of 100 F. The new fluid yielded an average of 6.75 percent air. With the cycled fluid, the air content ranged from 6.5 to 8.0 percent (Figure 63). Cycling the fluid did not appreciably change the air content as can be seen. Both dissolved and entrained air is reflected in these measurements. However, as the samples could not be evaluated immediately upon removal from the system, it is suspected that the entrained air migrated to the fluid surface and was released. An indication of this was the formation of an air bubble above the sample in a previously full container. So, the values obtained are probably most representative of the air dissolved in the fluid.

AIR CONTENT DATA

WSX-6885 FLUID

READING NUMBER	NEW FLUID	CYCLED FLUID		
		CYCLED 22 MIN	4 HOUR DORMANT PERIOD	10 HOUR DORMANT PERIOD
1	6.0%	7.5%	7.0%	7.5%
2	6.5%	7.0%	8.0%	6.75%
3	6.0%	6.5%	6.5%	7.25%
4				* 8.0%

* VACUUM APPLIED FOR 5 MINUTES INSTEAD OF CUSTOMARY 2 MINUTES.

** SAMPLES OF CYCLED FLUID TAKEN AT A TEMPERATURE OF 100 F.

FIG. 63

V. CONCLUSIONS

Based on the data obtained, the following conclusions are realized.

1. Acceptable correlation was obtained between our bench measurements and published data for MIL-H-5606B and WSX6885 fluid. An accurate assessment of the Skydrol 500A data was difficult due to the inconsistency of the published data available.

2 The system measurements produced initial values which compared very favorably with the bench results for MIL-H-5606B and WSX-6885 fluids The data obtained with Skydrol 500A bracketed the initial values with the curve having a slightly greater slope.

3. The system measurements following pressurized dormant periods yielded the most accurate correlation with the initial system values and subsequently the bench and published values.

4. In measurements for a flowing fluid, the method employed also produced acceptable results for both WSX-6885 and Skydrol 500A fluids.

5. For conditions of continuous demand and pressurized dormant periods, which exist in flight control systems operations, the fluid bulk modulus does not vary appreciable from published data obtained by the Pressure-Volume-Temperature method.

6. For aircraft operating periods with the system unpressurized, as in utility systems, the fluid bulk modulus is low initially but approaches the published value within the first moments of system actuation. Therefore, for design purposes, the published value would be the most accurate.

VI. REFERENCES

1. "Isothermal Secant and Tangent Bulk Modulus of Selected Hydraulic Type Fluids to 750 F and 10,000 psig," Vern Hopkins, Donnel R. Wilson, Calvin Bloze, Midwest Research Institute presented at ASME Lubrication Symposium, June 3-5, 1963.

2. "High Intensity Ultrasonics," Basil Brown, John E. Goodman, D. Van Nostrand Company, Inc., New Jersey, 1965

3. "Mechanics of Fluids," Irving H. Shames, McGraw-Hill Book Company, Inc., New York, 1962

4 "Fluid Mechanics," Victor L. Streeter, McGraw-Hill Book Company, Inc., New York, 1962

5. Boeing Document D6-1?726TN, Physical and Chemical Evaluation of Candidate Hydraulic Fluids for Supersonic Aircraft (September 8, 1964 through January 31, 1967), March 9, 1967.

6. Boeing Document D6-51225TN, "Analytical Method of Obtaining Fluid Tangent Bulk Modulus from a Single Secant Bulk Modulus Value by Least Squares Curve Fit," August 10, 1967.

7 Monsanto Technical Bulletin No. AV-1, "Skydrol 500A and Skydrol 7000 Fire Resistant Aircraft Hydraulic Fluids," revised July, 1964.

APPENDICES

APPENDIX A

Derivations and Calculations

AD 1546 D

RELATIONS FOR CALCULATION OF BULK MODULUS
OF A FLOWING FLUID

FROM REFERENCE 4:

$$a = \frac{\sqrt{K/\rho}}{\sqrt{1 + \frac{KDC_1}{Et'}}}$$

SQUARING

$$a^2 = \frac{K/\rho}{1 + \frac{KDC_1}{Et'}}$$

$$\rho a^2 + \frac{KD\rho a^2 C_1}{Et'} = K$$

$$\rho a^2 = K\left[1 - \frac{D\rho a^2 C_1}{Et'}\right]$$

$$\frac{\rho a^2}{1 - \frac{D\rho a^2 C_1}{Et'}} = K$$

$$\frac{\rho a^2 Et'}{Et' - D\rho a^2 C_1} = K$$

$$K \doteq \bar{B}_s$$

$$\bar{B}_s = \frac{\rho a^2 Et'}{Et' - D\rho a^2 C_1}$$

WHERE:

a - WAVE SPEED - FT/SEC

ρ - FLUID DENSITY - SLUG/FT^3

D - INSIDE TUBE DIAMETER - FT

t - TUBE THICKNESS - FT

E - MODULUS OF ELASTICITY, ... -

RELATION (CON'T)

C_1 - TUBE RESTRAINT CONSTANT - DEPENDENT UPON MOUNTING OF TUBE - FOR THIS TEST FIXTURE $C_1 = 0.91$

CLOSURE TIME FOR RAPIDLY CLOSING VALVE.

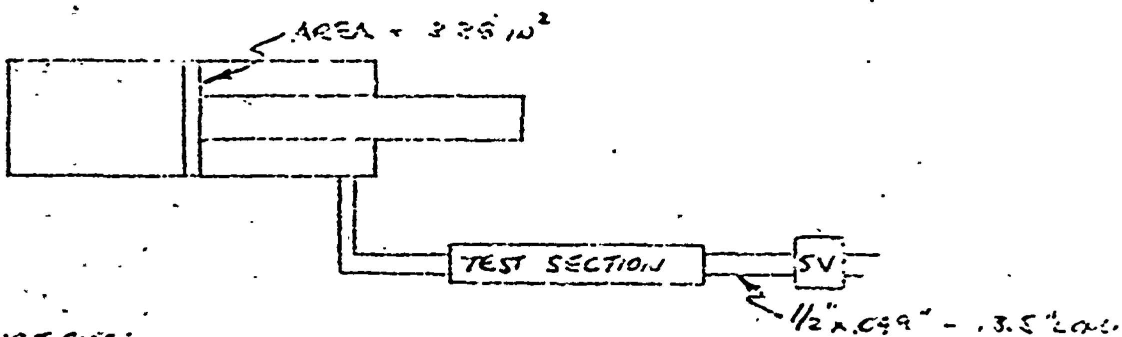
$t = 2L/a$

WHERE : t = TIME - SEC

L = LENGTH OF TUBE - FT

a = WAVE SPEED - FT/SEC

CALCULATION OF NEW OIL IN TEST SECTION
WITH ACTUATOR CYCLING



CONDITIONS:

NULL - 2.48" ROD EXPOSED

FULL EXTEND - 4.40" ROD EXPOSED

FULL RETRACT - 0.50" ROD EXPOSED

$$Vol_{TUBE} = \frac{\pi}{4}(.402)^2(13.5) = 1.714\ in^3$$

$$Vol_{TEST\ SECTION} = (395cc)(6.102 \times 10^{-2}\ in^3/cc) = 24.1\ in^3$$

RETRACT: (FROM NULL)

STROKE = 2.48 - 0.5 = 1.98 IN

$A = 3.35\ in^2$

$Vol = (3.35)(1.98) = 6.69\ in^3$

$V_{OIL-TS} = 6.69 - 1.714 = 4.976\ in^3 \approx 5.0\ in^3$

EXTEND: (FROM NULL)

STROKE = 4.40 - 2.48 = 1.92 IN

$A = 3.35\ in^2$

$Vol = (3.35)(1.92) = 6.49\ in^3$

$V_{OIL-TS} = 6.49 - 1.714 = 4.776 = 4.8\ in^3$

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APR.				THE BOEING COMPANY RENTON, WASHINGTON	88

NEW OIL (CONT)

RETRACT: (FROM FULL EXTEND)

STROKE: $9.40 - 5.5 = 3.90$ IN

$A = 3.38$ IN^2

$VOL = (3.38)(3.90) = 13.2$ IN^3

$V'_{OIL-TS} = 13.2 - 1.714 = 11.486 = 11.5$ IN^3

EXTEND: (FROM FULL RETRACT)

$V_{OL} = 13.2$ IN^3

$V_{OIL-TS} = -11.5$ IN^3

RETRACT: (FULL EXTEND TO NULL)

STROKE: $4.40 - 2.48 = 1.92$ IN

$VOL = (3.38)(1.92) = 6.49$ IN^3

$V_{OIL-TS} = 6.49 - 1.714 = 4.776 = 4.8$ IN^3 NET NEW OIL AFTER TWO FULL CYCLES - ASSUMING NO MIXING

APPENDIX B

Miscellaneous

AD 1546 D

Monsanto
COMPANY

St. Louis, Missouri

September 16, 1966

Mr. Wilson Hamilton
Material Engineering Dept.
The Boeing Company
Renton, Washington

Dear Wilson:

Sometime ago Boeing requested that we supply your company with data relating to Skydrol 500A, Skydrol 500B and 5606. Specifically you requested viscosities, densities, pressure viscosities, bulk moduli, and vapor pressures for these products. In addition you requested air solubility and speed of sound data for Skydrol 500A. Attached to this letter our a number of data sheets on which you will find the requested information. If we can be of any further service to you on this subject please let us know.

Very truly yours,

F. H. Langenfeld

/cc

Attachments

cc: Mr. Jerry Johnson
Materiel Engineering Dept.

Mr. Al Bremer
Engineering Staff

MONSANTO COMPANY
ORGANIC DIVISION RESEARCH DEPARTMENT

Miscellaneous Monsanto Data on Skydrol 500 and MIL-H-5606

		Skydrol 500		MIL-H-5606	
		A	B	A	B
1. Viscosity, CS at	-40°F	562	761	471	469
	0°F	100.9	105.4	103.6	97.1
	100°F	11.70	11.79	14.56	14.31
	210°F	3.91	3.96	5.24	5.23
2. Density, gm/ml. at	-40°F	1.1213	1.1203	0.9042	0.9109
	0°F	1.1023	1.1007	0.8881	0.8984
	100°F	1.0545	1.0532	0.8487	0.8542
	210°F	1.0025	1.0010	0.8051	0.8104
3. Bulk Modulus, Kpsi at (Isothermal Secant, 0-7 Kpsig)	100°F	264	278	229	229
	200°F	220	223	186	179
	300°F	165	178	139	139
4. Pressure Viscosity, CS at (100°F)	2 Kpsig	13.9	13.4	19.8	17.3
	4 Kpsig	16.5	15.0	25.9	21.0
	6 Kpsig	19.4	16.8	34.8	25.5
5. Vapor Pressure, mmHg at	50°F	1.2	3.0	c. 0.8	-
	150°F	15.2	44	6.9	42
	250°F	77	235	30.5	77

D. R. Miller

MONSANTO COMPANY
ORGANIC DIVISION RESEARCH DEPARTMENT

Miscellaneous Monsanto Data on Skydrol 500A

6. Air Solubility in Skydrol 500A at 100°F

Vol. % air (68°F, 1 atm. abs.) = 0.54 p(psia)

PPM (wgt.) air = 6.4 p(psia)

Estimated accuracy of constants ± 5%

Measurement range 14.7 to 115 psia

7. Sonic Velocity of Skydrol 500A at atmospheric pressure

$$C \text{ (meters/sec.)} = 1435 - 3.25\, t(°C)$$
$$= 1493 - 1.81\, t(°F)$$

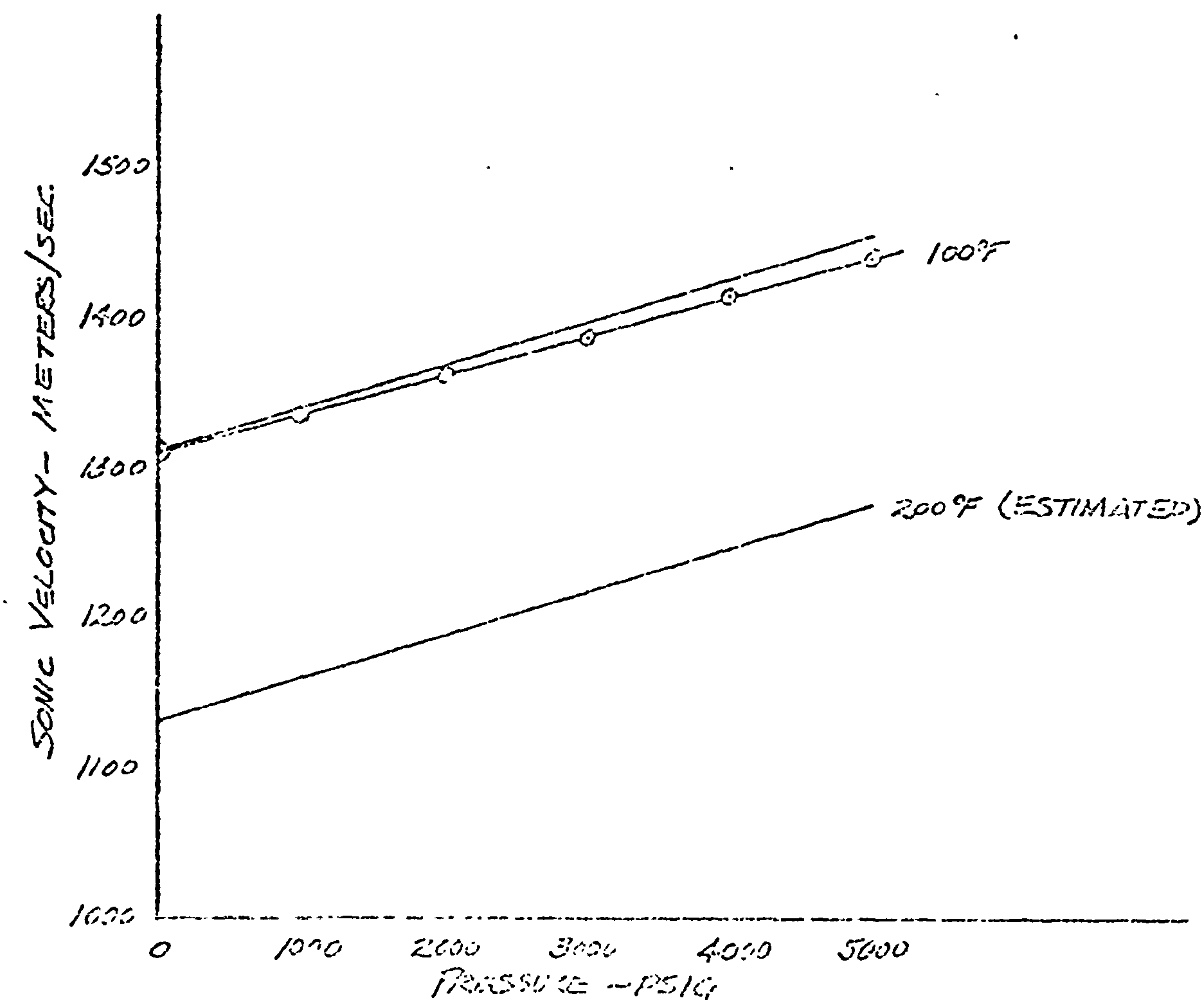
Estimated accuracy of constants ± 1%

Measurement range 0 - 100°C

8. Sonic Velocity of Skydrol 500A at 100°F, meters/sec.

Pressure, psig	Sample Air-Saturated at 100°F and 0 psig (as is)	Sample Air-Saturated at 100°F and 100 psig
0	1310	-
100	-	1312
1000	1335	1340
2000	1361	1367
3000	1387	1397
4000	1415	1425
5000	1440	1453

D. R. Miller



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APR					THE BOEING COMPANY	PAGE 94
APR						

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"TECHNIQUES FOR MEASURING AND
REMOVING AIR FROM HYDRAULIC
CONTROL SYSTEMS"

V. G. Magorien, Chief Engineer
Seaton-Wilson Mfg. Co., Inc.
Burbank, California

Presented before the 22nd annual meeting of the National Conference on
Fluid Power, October 20 - 21, 1966

D6-58362TN

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

"TECHNIQUES FOR MEASURING AND REMOVING AIR FROM HYDRAULIC CONTROL SYSTEMS"

I General

IT IS A GENERALLY ACCEPTED FACT, THAT HYDRAULICS IS AN EXCELLENT METHOD OF POWER TRANSMISSION. THE PRIME REASON FOR THIS ACCEPTANCE IS IT'S INHERENT STIFFNESS. DUE TO THE VERY HIGH BULK MODULUS OF MOST FLUIDS, THE POSITIVE, PRECISE POSITIONING OF A RAM OR A SHAFT SHOULD BE A CERTAINTY; BUT IS IT?

TRUE, ONE CANNOT SAY THE SYSTEM IS "STIFF" UNLESS IT IS COMPLETELY FLUSHED OF AIR; HOWEVER, ONCE THAT IS ACCOMPLISHED, THE SYSTEM SHOULD BE "SOLID." THE WORD SHOULD IS USED BECAUSE THE STIFFNESS OF A SYSTEM IS RARELY MEASURED IN A QUANTITATIVE MANNER. THIS OVERSIGHT MIGHT BE EXPLAINED AWAY BY CALLING IT AN INTERFACE PROBLEM. THAT IS, IT IS THE POINT WHERE THE DESIGNER LEAVES OFF AND THE TECHNICIAN TAKES OVER. TOO OFTEN, IT IS THE RESPONSIBILITY OF THE TECHNICIAN TO KNOW WHEN TO STOP FILLING AND FLUSHING. IT IS SOMEWHAT ANTI-CLIMACTICAL TO GATHER A LARGE NUMBER OF MEASUREMENTS ON INDIVIDUAL COMPONENTS; AND THEN, AT THE LAST MOMENT, NOT MEASURE THAT WHICH WAS DESIRED IN THE FIRST PLACE!

THE PURPOSE OF THIS REPORT IS TO DESCRIBE TECHNIQUES AND DEVICES FOR MEASURING AND REMOVING AIR IN ORDER TO INSURE A "STIFF," HIGH RESPONSE SYSTEM.

II Sample Air Tests

IN ORDER TO OBTAIN DATA WHICH WOULD BE BOTH SIMPLE, YET MEANINGFUL, A CONVENTIONAL, DOUBLE-ENDED ACTUATOR (SEE FIG. I) WAS CONNECTED TO A 1 GPM, 3000 PSI, MIL-H-5606, HYDRAULIC SYSTEM. IT WAS THEN INSTRUMENTED WITH A DEVICE WHICH WOULD MEASURE THE COMPRESSIBILITY OF ANY AIR-OIL MIXTURE. THE MECHANICS OF THE INSTRUMENT WILL BE EXPLAINED LATER.

STARTING WITH AN EMPTY ACTUATOR, FLUSHING BEGAN AT LOW PRESSURE; I. E., APPROXIMATELY 300 PSIG. THE CYLINDER WAS CYCLED BY MEANS OF A FOUR-WAY VALVE WITH FLOW PASSING THROUGH AN .032 DIAMETER ORIFICE AT THE CYLINDER PORT. THE PURPOSE OF THE ORIFICE WILL BE EXPLAINED LATER. AFTER EVERY SIX CYCLES, THE TEST STAND WAS SHUT DOWN AND AN AIR MEASUREMENT TAKEN. A GRAPH WAS MADE, ILLUSTRATING THE DECREASE OF AIR VERSUS FLUSHING CYCLES. (SEE FIG. II.)

IN ADDITION, THE CYLINDER WAS PERIODICALLY PRESSURIZED TO 1000, 2000 AND 3000 PSIG. THE AMOUNT OF FLUID REQUIRED TO ACHIEVE THESE PRESSURES WAS MEASURED AND RECORDED. (SEE FIG.III.)

THE EFFECTIVE BULK MODULUS @ 3000 PSIG WAS THEN COMPUTED FOR

FOR VARIOUS AIR CONTENTS USING THE VALUES OBTAINED. (SEE FIG. IV.) NEEDLESS TO SAY, IT WAS QUITE STARTLING TO DISCOVER THAT, WITH A CONTENT OF ONLY .17% OF COMPRESSIBLE AIR, THE THEORETICAL BULK MODULUS WAS CUT IN HALF! THE FIRST INCLINATION IS TO TAKE SOLACE FROM THE FACT THAT, AT THE LEAST, CAREFUL FLUSHING HAD BROUGHT THE COMPRESSIBLE AIR CONTENT DOWN TO 0.2%. UNFORTUNATELY, THIS VALUE DID NOT REMAIN AT 0.2%. AFTER FLUSHING, THE TEST STAND PRESSURE WAS INCREASED TO 1000 PSIG. THE PURPOSE OF THE ORIFICE, UPSTREAM OF THE CYLINDER, WAS TO SIMULATE THE AREA OF AN .032 DIAMETER VALVE OPENING. AFTER ONE-HALF CYCLE, AN AIR MEASUREMENT WAS MADE AND FOUND TO BE 0.8%! AFTER THE SECOND CYCLE, IT WAS 1.6% AND SO ON. (SEE FIG. V.) IN SHORT, DISSOLVED AIR CAME OUT OF SOLUTION AND COLLECTED IN THE ACTUATOR. IT IS THIS FORM OF AIR WHICH NEGATES NORMAL FILL AND FLUSH TECHNIQUES. BEFORE CONTINUING WITH DESCRIPTIONS OF AIR MEASURING AND AIR SEPARATING DEVICES, SOME DEFINITIONS ARE IN ORDER.

III FORMS OF AIR

FREE AIR: FREE AIR IS THAT WHICH IS TRAPPED, BUT NOT TOTALLY IN CONTACT WITH A FLUID. IT IS NEITHER ENTRAINED NOR DISSOLVED. AN EXAMPLE OF FREE AIR WOULD BE AN "AIR-POCKET" IN A SYSTEM.

ENTRAINED AIR: ENTRAINED AIR IS THAT WHICH IS SUSPENDED IN A FLUID AND NORMALLY EXISTS IN THE FORM OF SMALL BUBBLES.

DISSOLVED AIR: DISSOLVED AIR IS THAT WHICH ENTERS INTO SOLUTION WITH A FLUID. SINCE IT IS NEITHER FREE NOR ENTRAINED AIR, IT DOES NOT BEHAVE ACCORDING TO BOYLE'S LAW. IT DOES, HOWEVER, OBEY HENRY'S LAW, WHICH STATES THAT "THE WEIGHT OF GAS DISSOLVED IS PROPORTIONAL TO THE PRESSURE." IT CAN BE REMOVED BY TWO DIFFERENT MEANS: SUBJECTING THE FLUID TO A REDUCED PRESSURE AND/OR RAISING THE FLUID TEMPERATURE. ITS PRESENCE OR ABSENCE DOES NOT AFFECT THE VOLUME OF THE FLUID.

A PICTORIAL EXAMPLE OF THE THREE FORMS OF AIR IS SHOWN IN FIG. VI.

IV ADDITIONAL DATA ON DISSOLVED AIR

SEATON-WILSON HAS MADE DISSOLVED AIR MEASUREMENTS ON SEVERAL, COMMON, HYDRAULIC FLUIDS AND THE RESULTS ARE SHOWN IN FIG. VII.

IT SHOULD BE EMPHASIZED THAT NEITHER THE PRESENCE NOR THE ABSENCE OF DISSOLVED AIR AFFECTS THE VOLUME OF THE OIL; AND

TEST DATA SEEMS TO INDICATE THAT THERE IS NO EFFECT ON BULK MODULUS, PROVIDING THE AIR IS IN SOLUTION. THESE FACTS, AT FIRST, APPEAR PARADOXICAL; HOWEVER, IF ONE VISUALIZES A CONTAINER FILLED TO THE BRIM WITH MARBLES, WHICH REPRESENT THE OIL MOLECULES, IT IS POSSIBLE TO POUR IN FLUID, REPRESENTING AIR, AROUND THEM, OR REMOVE THE FLUID WITH NO CHANGE IN VOLUME. THE WEIGHT OF THE CONTAINER CHANGES, BUT NOT THE VOLUME. THE APPEARANCE AND DISAPPEARANCE OF DISSOLVED GASES , IN THE FORM OF ENTRAINED AIR, IS AN INTERESTING, BUT ELUSIVE, PHENOMENON.

ACCELERATING FLUID THROUGH AN ORIFICE CAUSES A LOCAL, STATIC PRESSURE DROP. IF THE PRESSURE DROPS BELOW ATMOSPHERIC PRESSURE, DISSOLVED GAS APPEARS IN THE FORM OF TINY BUBBLES. PROVIDING THESE BUBBLES DO NOT CONGLOMERATE INTO LARGER BUBBLES, AND THE VELOCITY OF THE FLUID IS KEPT LOW, MOST OF THE AIR BUBBLES ARE READSORBED DOWNSTREAM WHERE THE STATIC PRESSURE IS GREATER THAN ATMOSPHERIC. THIS PHENOMENON AGREES WITH HENRY'S LAW. THERE IS AN EXCEPTION TO THIS CONDITION, HOWEVER; AND THAT IS, AS THE FLUID IS ACCELERATED CLOSE TO ITS SONIC VELOCITY, THE AIR BUBBLES EXPAND TO LARGER SIZES AND ARE RELUCTANT TO GO BACK INTO SOLUTION DESPITE SUBSEQUENT EXPOSURE TO HIGHER PRESSURES. TOO, EROSION OF MATERIALS HAS BEEN KNOWN TO TAKE PLACE IN THE VICINITY OF BUBBLE GROWTH. IT IS NOT THE PURPOSE OF THIS REPORT, HOWEVER, TO INVESTIGATE EROSION.

V DESCRIPTION OF AIR MEASURING EQUIPMENT

SINCE AIR CAN EXIST IN EITHER COMPRESSIBLE OR INCOMPRESSIBLE FORMS, IT IS NECESSARY TO HAVE TWO, DISTINCTLY DIFFERENT MEANS OF MEASURING ITS PRESENCE. TO FILL THESE NEEDS, SEATON-WILSON MANUFACTURING COMPANY HAS DEVELOPED TWO INSTRUMENTS:

A. A-400 "AIRE-OMETER" (SEE FIG. VIII.)

THIS DEVICE IS USED TO MEASURE COMPRESSIBLE AIR CONTENT. IN PRINCIPLE, IT TAKES ADVANTAGE OF AIR'S COMPRESSIBILITY. THE AIR IN A CLOSED SYSTEM IS PRESSURIZED TO A PREDETERMINED LEVEL, EITHER WITH ITS OWN FLUID OR FROM AN EXTERNAL SUPPLY. AFTER "ZEROING-OUT" THE INSTRUMENT, THE PRESSURE IS RELIEVED AND THE COMPRESSED FLUID IS ALLOWED TO EXPAND INTO A MANOMETER TUBE, WHERE IT IS MEASURED. BY MEANS OF BOYLE'S LAW, THE AMOUNT OF TRAPPED AIR CAN BE CALCULATED.

B. AD-4001 "AIRE-OMETER" (SEE FIG. IX.)

THIS DEVICE IS USED TO MEASURE DISSOLVED AIR CONTENT. IN PRINCIPLE, IT TAKES ADVANTAGE OF THE FACT THAT GAS WILL COME OUT OF SOLUTION WHEN EXPOSED TO A VACUUM. A SMALL FLUID SAMPLE IS TITRATED

FROM THE UPPER RESERVOIR INTO THE LOWER TUBE, USING MERCURY AS THE WORKING MEDIUM, AND THEN EXPOSED TO A VACUUM. AFTER THE GASES HAVE ESCAPED, THE AIR-FLUID MIXTURE IS PRESSURIZED TO ATMOSPHERIC PRESSURE AND THE VOLUME OF GAS MEASURED.

VI Description of Air Separation Equipment

To remove all three forms of air, Seaton-Wilson has developed an automatic air Separator. (SAF-1001 "SEPARATE-AIRE")(See FIG. X.)

Since degassing can only be accomplished in the presence of a vacuum; yet, a negative head in a reservoir results in pump cavitation, the fluid must be processed in a separate container. After the fluid has been degassed, it must then be pumped back up to system return pressure. To achieve this, the "SEPARATE-AIRE" uses an aspirator to both degas and jet-pump the processed fluid up to system return pressure. The "SEPARATE-AIRE" is placed in a system in parallel to the load, and thus operates at system pressure. (See FIG. XI.) Unless "valved-off" from the system, it will make a continual bleed or drain on the hydraulic horsepower provided by the pump.

Fluid, to be degassed, is introduced from the return side of the hydraulic circuit. Since unsaturated fluid is aspirated into the same stream, which is creating the vacuum, mixing occurs. The degassing process can now be seen to be a parasitic one, and a curve of dissolved air content versus running time of a "SEPARATE-AIRE" is an exponential one. (See FIG. XII for dissolved gas content of open and closed systems.)

After the degassing chamber has filled with air, float switches are used to sense the end of the cycle. The aspirator solenoid valve is shut off , and the vent solenoid valve opened. Degassing flow is allowed to continue, and since it is no longer being aspirated, filling occurs. The air is compressed to a pressure slightly above atmospheric pressure and venting begins again through a check valve. Float switches sense when total purging has been accomplished and the aspirator is reactivated to repeat the entire cycle.

VII Results of Air Removal

The hydraulic cylinder, described above, was tested while assembled in a system whose schematic is shown in FIG. XI. All of the compressible air measurements, shown in FIGS. II, III and IV were made with an A-400 "AIRE-OMETER." To evaluate the effects of air removal, the air-oil separator, described above, was allowed to operate for eight, 15 minute cycles. The reservoir fluid was covered by a floating piston

AND THE DISSOLVED AIR CONTENT OF THE FORMER WAS MEASURED BY MEANS OF AN AD-4001 "AIRE-OMETER." A CURVE OF DISSOLVED AIR CONTENT VERSUS RUNNING TIME IS SHOWN IN FIG. XII. THE ACTUATOR WAS THEN RECYCLED AT LOW PRESSURES, AS BEFORE, AND AIR MEASUREMENTS WERE TAKEN EVERY SIX CYCLES. (SEE FIG. XIII.)

IT IS WORTH NOTING THAT THE NUMBER OF FLUSHING CYCLES REQUIRED TO ACHIEVE A SPECIFIC LEVEL OF AIR CONTENT DIMINISHED.

THE SYSTEM PRESSURE WAS THEN RAISED, AS BEFORE, TO 1000 PSIG. TEN CYCLES WERE MADE AND NO ENTRAINED AIR APPEARED IN THE CYLINDER, NOR IN ANY PART OF THE SYSTEM. (SEE FIG. XIII.)

VIII CONCLUSIONS

THE CONCLUSIONS THAT WERE DRAWN FROM THE TESTS WERE BROKEN DOWN INTO FOUR SPECIFIC AREAS:

A. EFFECTS OF FLUSHING

THE EFFECT OF CONTINUOUS, HARD-OVER CYCLING UPON AIR CONTENT AGREED WELL WITH INTUITIVE RESULTS. IN FACT, THE FINAL VALUES ACHIEVED WERE FAR LOWER THAN WHAT WOULD BE IMAGINED FOR A CYLINDER WITH "BUILT-IN" AIR POCKETS.

ASSIDUOUS CYCLING CAN, THEREFORE, BE EXPECTED TO EFFECTIVELY PURGE ANY GIVEN SYSTEM OF AIR.

B. AERATION DUE TO DISSOLVED AIR

THE RESULTS OF THE HIGH PRESSURE CYCLING INDICATE THAT SYSTEMS USING AIR-SATURATED MIL-H-5606 FLUID, OR SIMILAR HYDRAULIC FLUIDS, AT PRESSURES OF APPROXIMATELY 1000 PSIG OR GREATER, CAN LOOK FORWARD TO THE GENERATION OF ENTRAINED AIR ACROSS ORIFICES IN THE SYSTEM.

LOW PRESSURE HARD-OVER CYCLING OF ACTUATORS CAN HELP REMOVE THE RESULTANT AIR IF THE CYLINDER TO VALVE LINES ARE SHORT.

CYLINDERS WORKING UNLOADED AND ONLY IN THE MID-STROKE RANGE, WITH INFREQUENT HARD-OVER TO HARD-OVER SIGNALS, CAN EXPECT INCREASING AIR CONTENTS WITH TIME.

C. BULK MODULUS

THE EFFECT OF AIR ON BULK MODULUS AGREED WELL WITH THEORY WHERE THE AIR CONTENT WAS 4% OR MORE (SEE APPENDIX). AT HIGH PRESSURE, THE CORRELATION FELL OFF AS AIR CONTENT DECREASED; I. E., ADDITIONAL VOLUME WAS REQUIRED BEYOND THAT DUE TO AIR AND FLUID COMPRESSIBILITY.

This effect could only be explained by the elasticity of the cylinder, O-ring, end cap, and thread clearances.

D. Effects of Deaeration

The effect of deaerating the system fluid was to prevent completely the generation of entrained air across the simulated valve orifice. Previous tests, conducted with unsaturated fluid, indicated accelerated purging also takes place due to the adsorption of small air bubbles. Further work is now underway to qualitatively define the reduction of pump noise and material erosion due to the use of unsaturated, hydraulic fluid.

E. General Conclusions

It is readily apparent, from the tests made, that several areas of performance can be improved as a direct result of deaerating the system fluid.

In regard to bulk moduli, a word of caution is necessary. The values shown are not s mitted as pragmatic numbers to be used with abandon. If anything, they point out that, for any specific system, actual measurements should be made rather than relying upon "text book" values.

APPENDIX

THE FOLLOWING CHART CONTAINS ACTUAL AND COMPUTED THEORETICAL VALUES OBTAINED FOR BULK MODULI TESTS:

(NOTE: 0.17, 0.97 AND 4.15 REFER TO AIR CONTENT IN %)

PRESS:	ACTUAL VOL. REQ'D			THEOR. VOL. REQ'D			DEVIATION - %		
	0.17	0.97	4.15	0.17	0.97	4.15	0.17	0.97	4.15
* 45	.040	.25	.99	.042	.206	.90	5	7	10.
500	--	.41	1.34						
1000	.240	.52	1.43	.186	.428	1.44	29	24	0.7
1500	---	.61	1.51						
2000	.460	.71	1.59	.303	.553	1.57	52	29	1.2
2500	--	.81	1.63						
3000	.670	.88	1.73	.415	.661	1.68	61	33	2.9

*NOTE: AIR CONTENT DETERMINED @ 45 PSIG BY MEANS OF BOYLE'S EQUATION: $V_1 = P_2 (V_1 - V_2)/ (P_2 - P_1)$

OR

$V_1 = 4 \Delta V/3$

E.G. $\Delta V = 4 \times .04/3 = .0533$ IN^3
% AIR = .053 x 100/32 = 0.166%; USE 0.17%
(ACTUAL CYLINDER VOLUME: 32 CUBIC INCHES)

INCREASING DEVIATIONS WITH DIMINISHING AIR CONTENTS ATTRIBUTED TO FIXED DISPLACEMENT OF CYLINDER, O-RINGS AND END CAP THREADS AT THE VARIOUS PRESSURES.

THEORETICAL VOLUME REQUIRED WAS COMPUTED AS FOLLOWS:
TOTAL VOLUME REQUIRED = CHANGE IN OIL VOLUME + CHANGE IN AIR VOLUME.

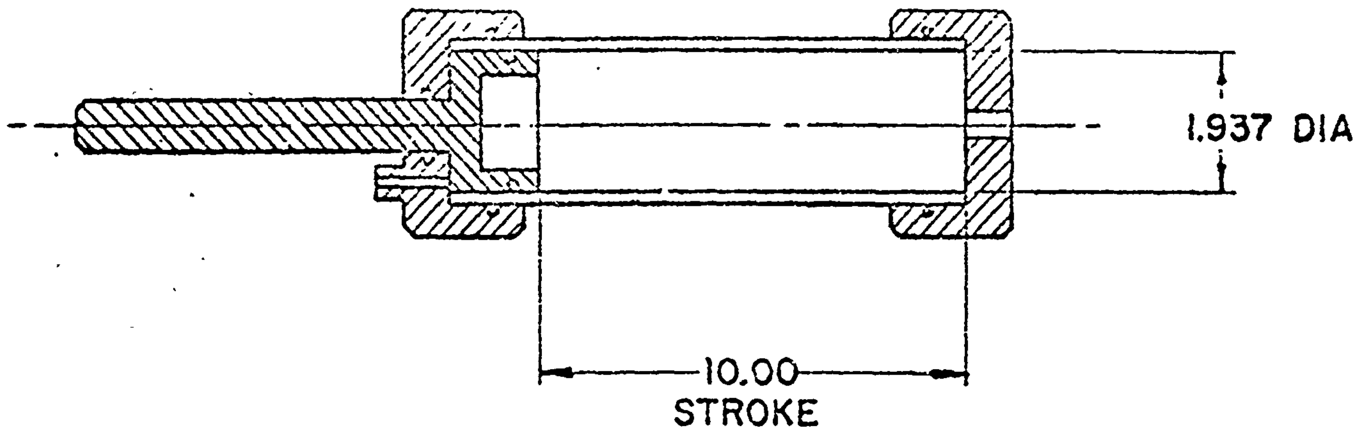
V TOTAL = (OIL VOLUME x PRESSURE/ BULK MODULUS) + AIR VOLUME x (1 - VOLUME RATIO)

PRESSURE	BULK MODULUS
45	220,000
1000	240,000
2000	250,000
3000	265,000

PRESSURE	VOLUME RATIO
45	.33
1000	.015
2000	.007
3000	.005

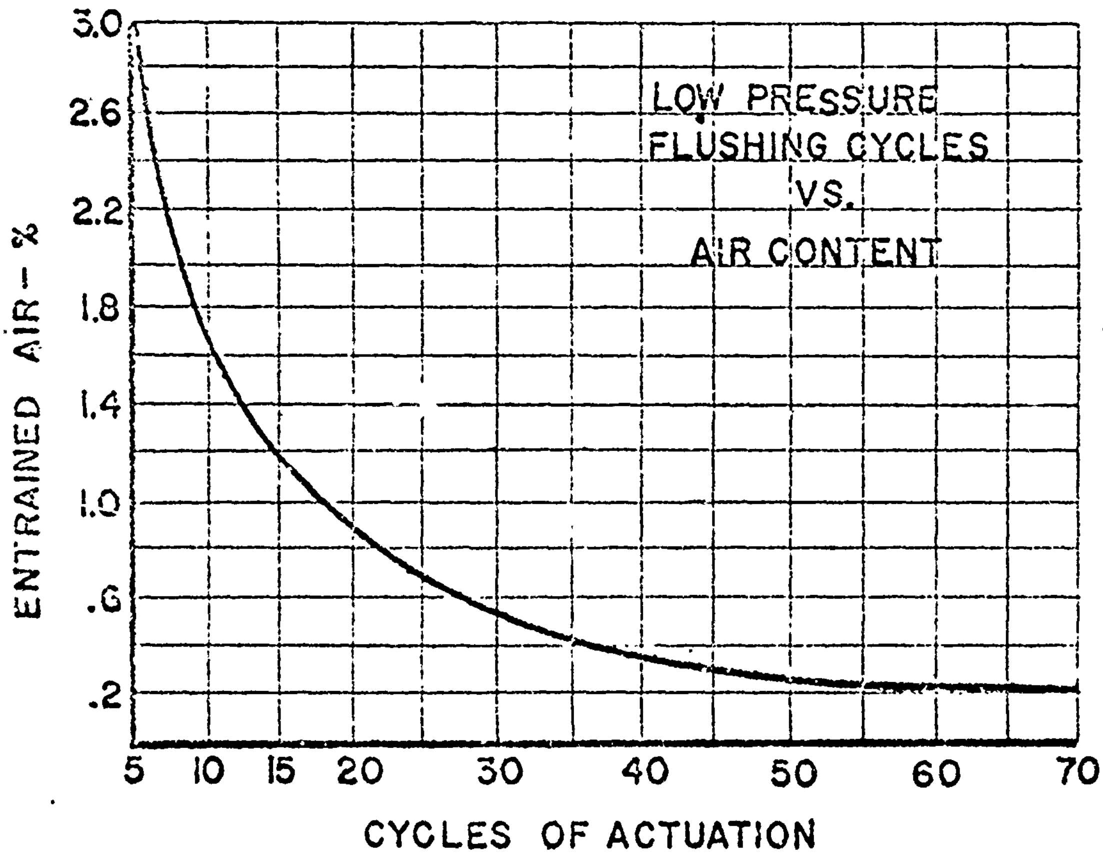
E.G. FOR 0.17% AIR: (AIR CONTENT: 054 IN^3; OIL CONTENT: 31.95 IN^3

ΔV TOTAL = (31.95 x 3000/265,000) + .054 (1 - .005)
= .362 IN^3 + .053 IN^3
= 0.415 CUBIC INCHES (THEORETICAL VOLUME REQUIRED)



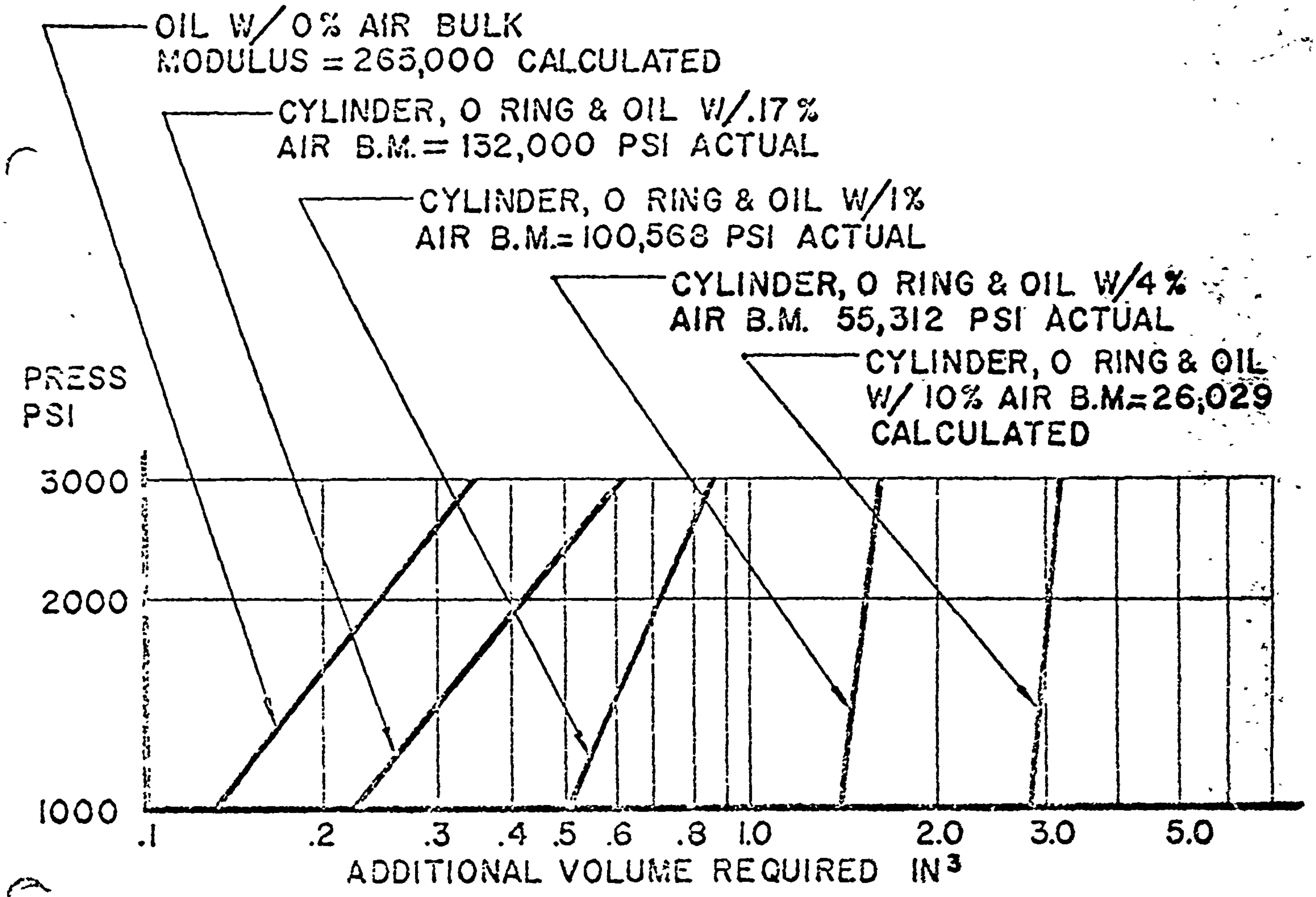
TEST CYLINDER

FIG. I



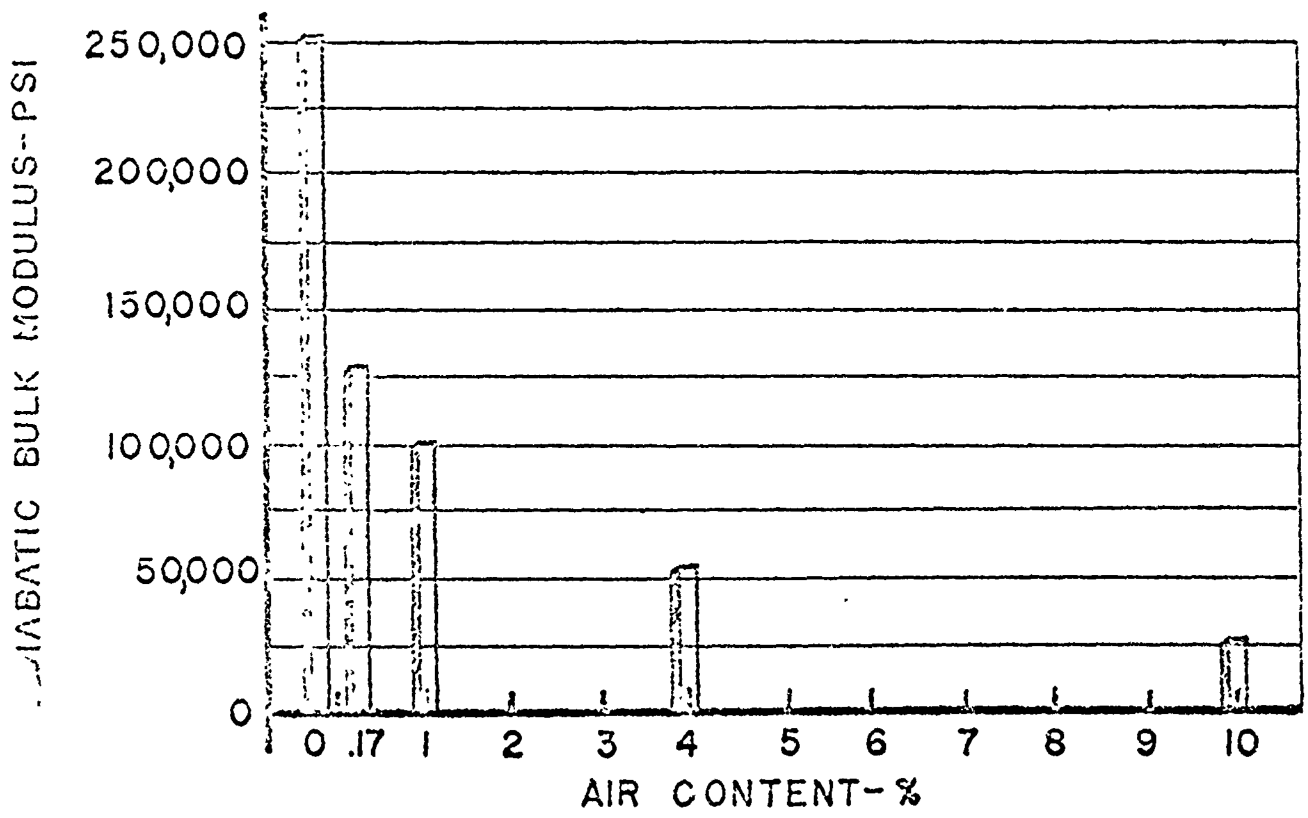
FLUSHING CYCLES VS. AIR CONTENT

FIG. II



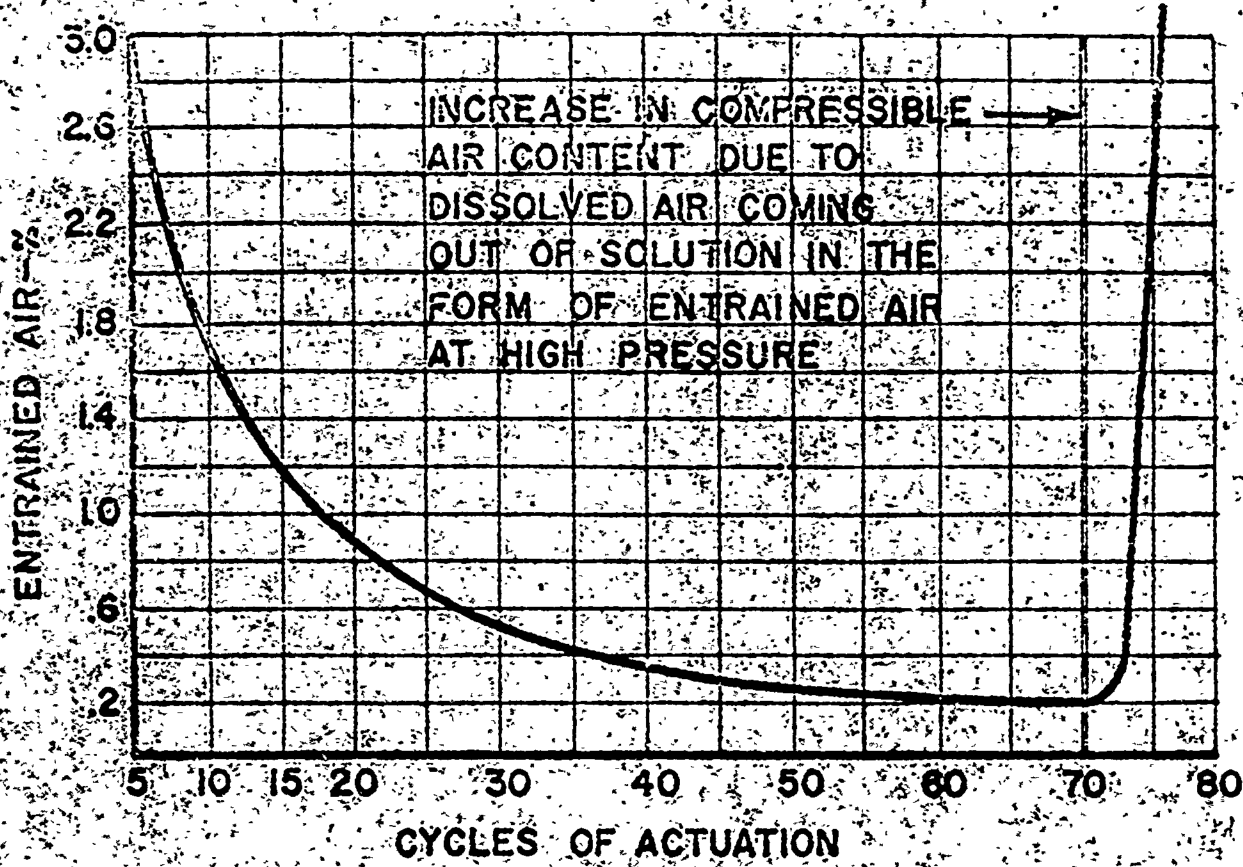
CURVES OF OIL VOLUMES REQUIRED TO PRODUCE VARIOUS CYLINDER PRESSURES

FIG. III



EFFECTIVE BULK MODULUS AT VARIOUS AIR CONTENTS

FIG. IV



AIR CONTENT GENERATED FROM DISSOLVED AIR

FIG. V

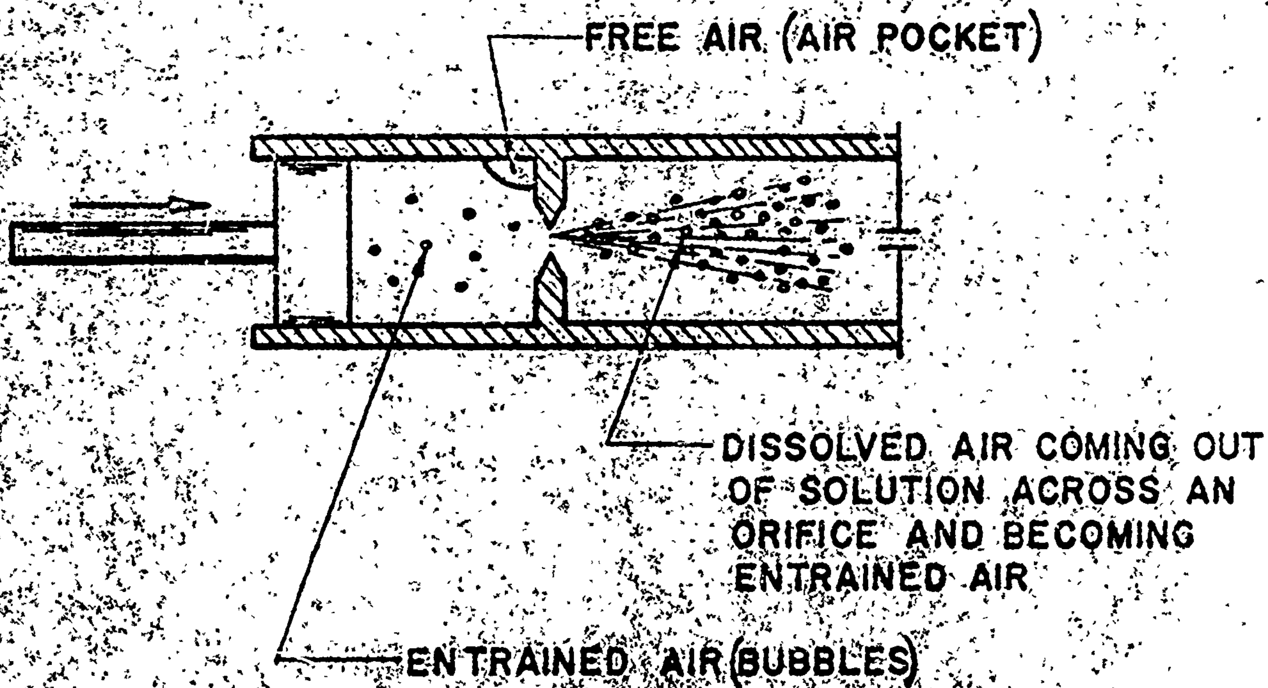


ILLUSTRATION OF THE THREE FORMS OF AIR

FIG VI

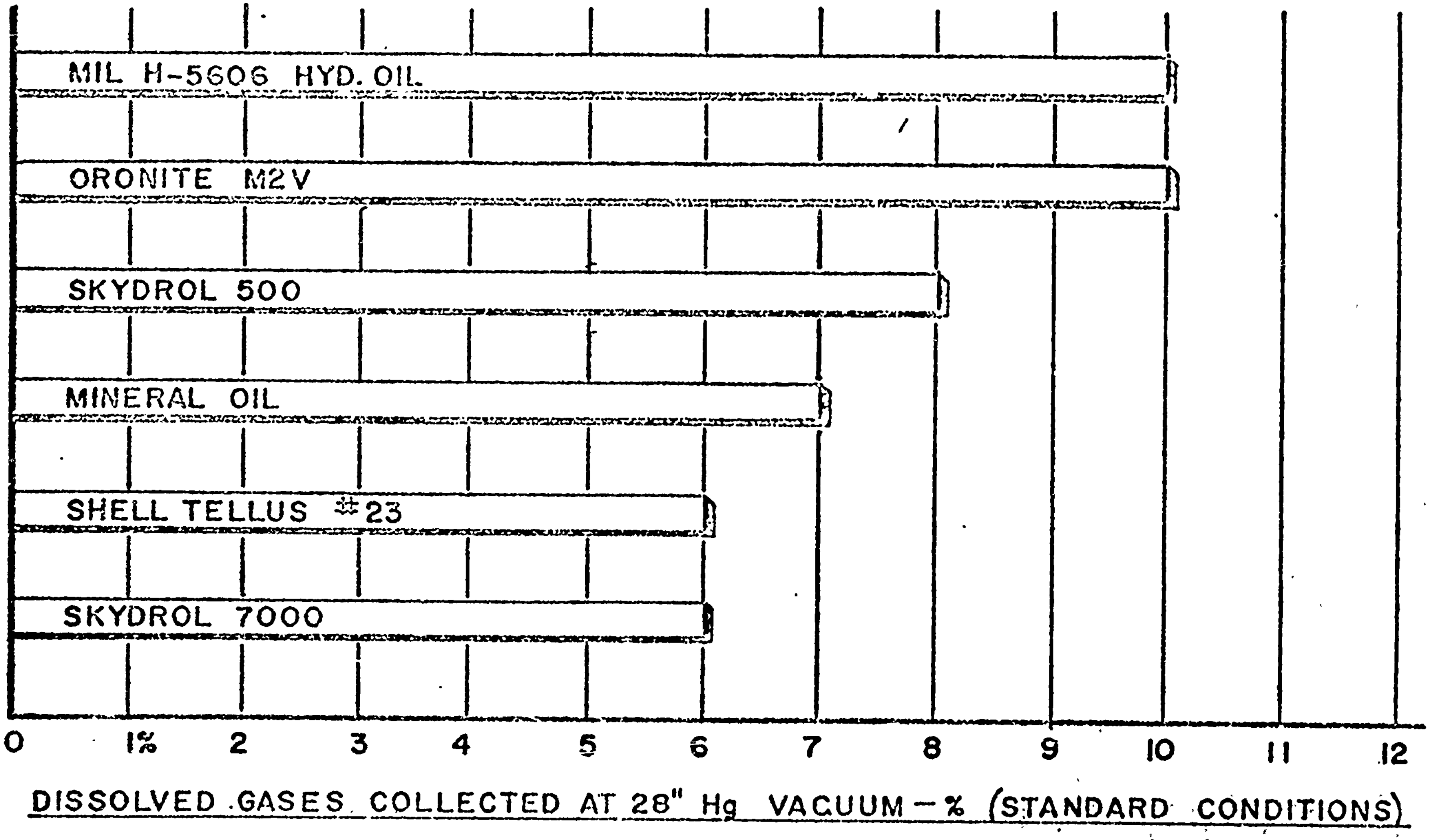
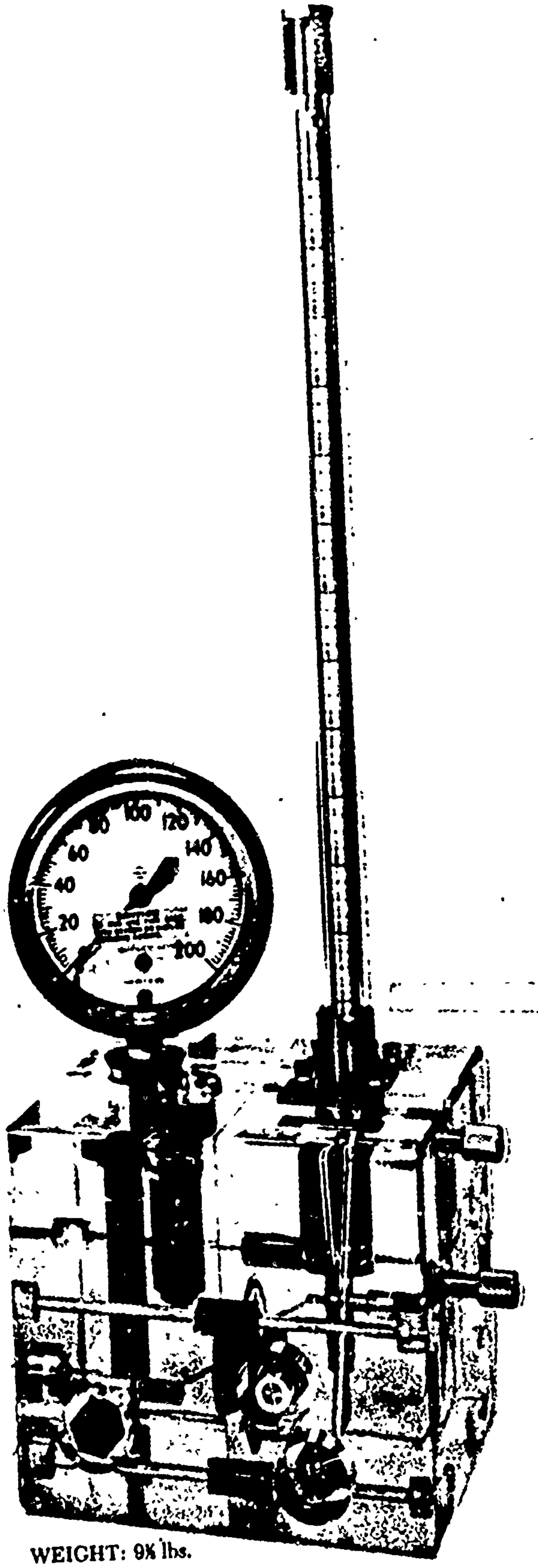

MIL H-5606 HYD. OIL
ORONITE M2V
SKYDROL 500
MINERAL OIL
SHELL TELLUS #23
SKYDROL 7000
0
1%
2
3
4
5
6
7
8
9
10
11
12
DISSOLVED GASES COLLECTED AT 28" Hg VACUUM — % (STANDARD CONDITIONS)

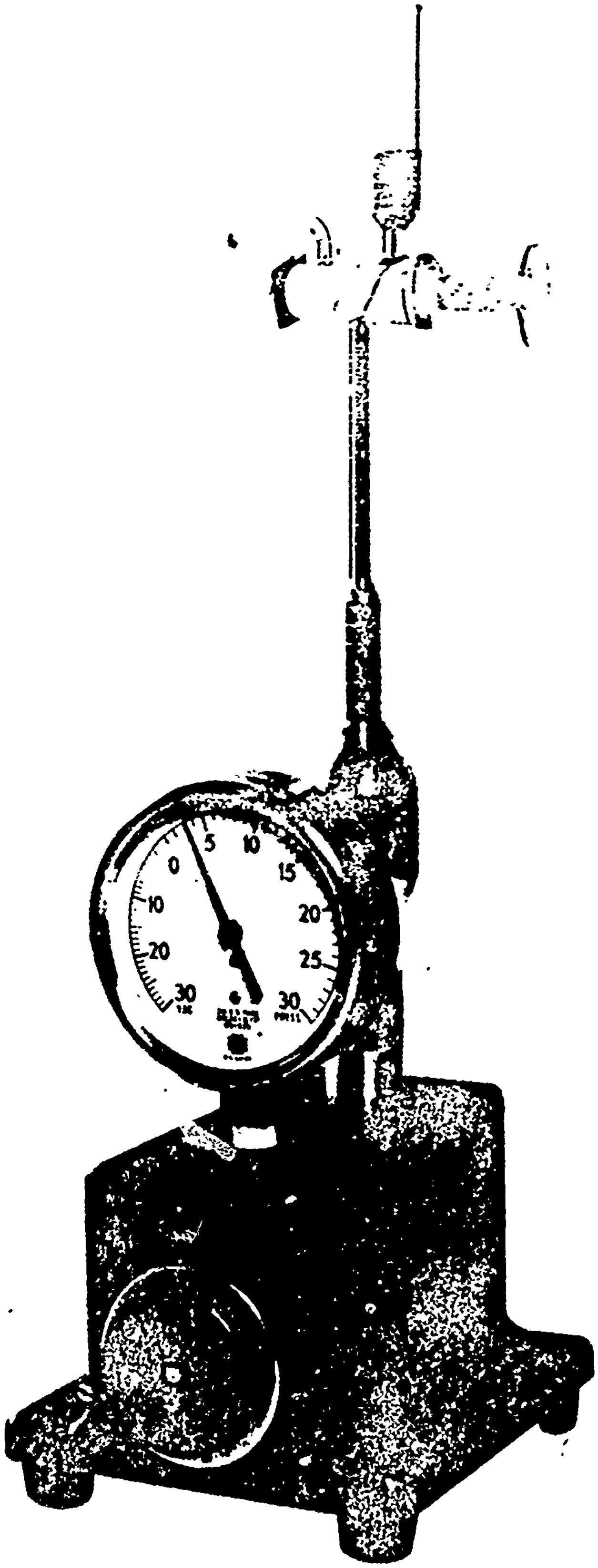
FIG. VII



WEIGHT: 9½ lbs.

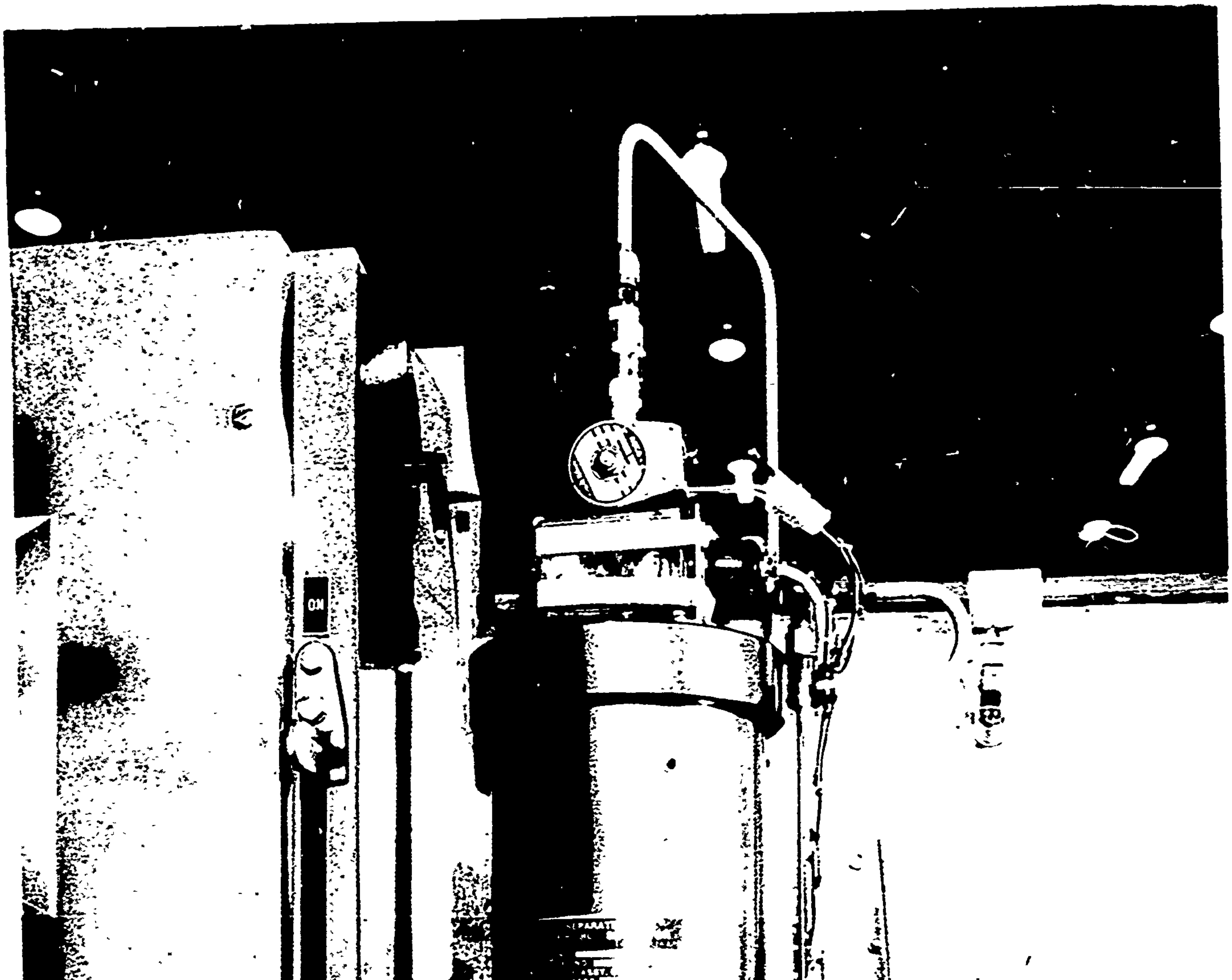
A-400 "AIRE-OMETER"

FIG. VIII



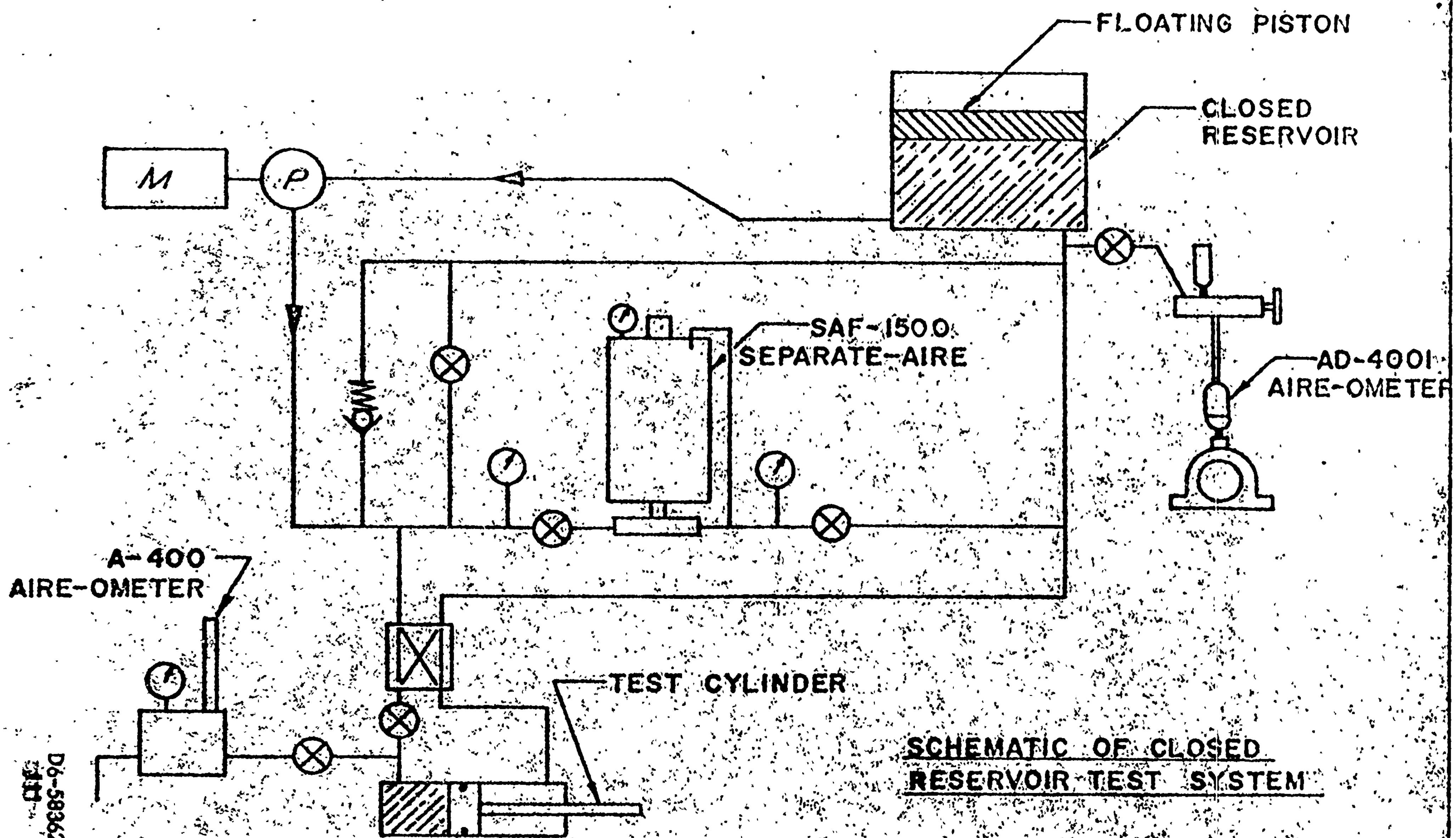
AD-4001 "AIRE-OMETER"

FIG. IX



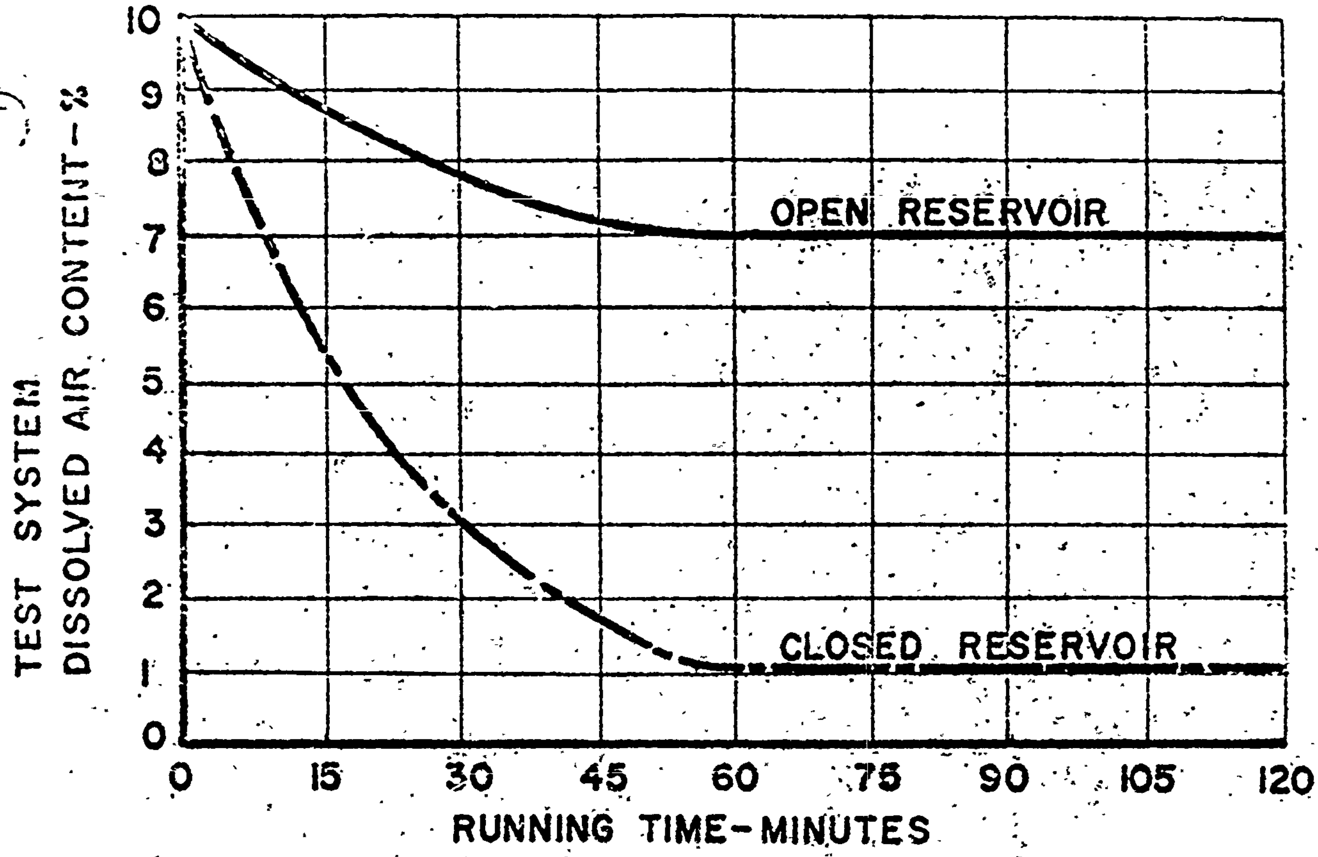
SAF-1001 "SEPARATE-AIRE"

FIG X

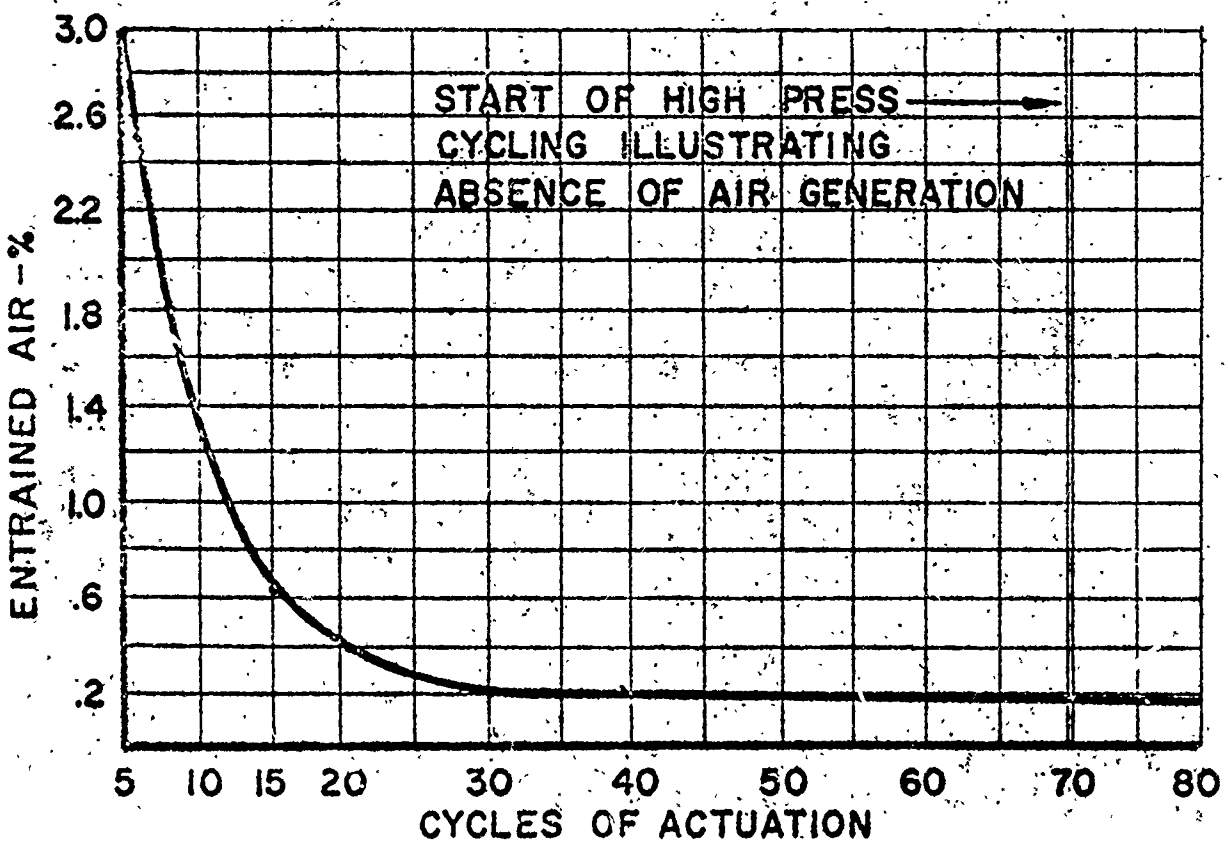


SCHEMATIC OF CLOSED RESERVOIR TEST SYSTEM

FIG XI



SYSTEM DISSOLVED AIR CONTENT VS. RUNNING TIME
FIG XII



CYLINDER AIR CONTENT WHEN FLUSHED WITH UNSATURATED OIL
FIG XIII

LIST OF ILLUSTRATIONS

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LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ACTIVE PAGES

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REVISIONS			
REV SYM	DESCRIPTION	DATE	APPROVAL

AD 1546 C

REV SYM